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Wind energy technology and current status: a review

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Abstract

The paper provides an overview of the historical development of wind energy technology and discusses the current status of grid-connected as well as stand-alone wind power generation worldwide. During the last decade of the 20th century, grid-connected wind capacity worldwide has doubled approximately every three years. Due to the fast market development, wind turbine technology has experienced an important evolution over time. An overview of the different design approaches is given and issues like power grid integration, economics, environmental impact and special system applications, such as offshore wind energy, are discussed. Due to the complexity of the wind energy technology, however, this paper mainly aims at presenting a brief overview of the relevant wind turbine and wind project issues. Therefore, detailed information on further readings and related organisations is included. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The power of the wind has been utilised for at least the past 3000 years. Until the early 20th century wind power was used to provide mechanical power to pump water or to grind grain. At the beginning of modern industrialisation, the use of the fluctuating wind energy resource was substituted by fossil fuel fired engines or the electrical grid, which provided a more consistent power source.

In the early 1970s, with the first oil price shock, the interest in the power of the wind re-emerged. This time, however, the main focus was on wind power providing electrical energy instead of mechanical energy. This way, it became possible to provide a reliable and consistent power source by using other energy technologies, via the electrical grid, as a back-up.

The first wind turbines for electricity generation had already been developed at the beginning of the 20th century. The technology was improved step by step since the early 1970s. By the end of the 1990s, wind energy has re-emerged as one of the most important sustainable energy resources. During the last decade of the 20th century, worldwide wind capacity has doubled approximately every 3 years. The costs of electricity generated from wind power have fallen to about one-sixth since the early 1980, and the trend seems to continue. Some experts predict that the cumulative capacity will be growing worldwide by about 25% per year until 2005 and cost will be dropping by an additional 20–40% during the same time period ([10], vol. 15, no. 5, p. 8).

Wind energy technology itself also moved very fast towards new dimensions. At the end of 1989, a 300 kW wind turbine with a 30-m rotor diameter was state-of-the-art. Only 10 years later, 1500 kW turbines with a rotor diameter of around 70 m are available from many manufacturers. The first demonstration projects using 2 MW wind turbines with a rotor diameter of 74 m was installed before the turn of the century. Four and five MW wind turbines are expected to become available in 2001 or 2002 (see also Table 1).

This fast development of the wind energy market as well as of the technology has large implications on research, education as well as on professionals working

for electric utilities or the wind energy industry. It is important to mention that about 80% of the worldwide wind capacity is installed in only five countries: Germany, USA, Denmark, India and Spain. Hence, most of the wind energy knowledge is based in these countries. The use of wind energy technology, however, is fast spreading to other areas in the world. Hence, the available information must also be spread around the world. That is the main purpose of this review paper. However, despite the fact that wind energy has already been utilised for 3000 years, it is a very complex technology. The technology involves technical disciplines such as aerodynamics, structural dynamics, mechanical as well as electrical engineering. Due to the complexity of the wind energy technology this review paper on wind energy is not able to cover all related topics in great detail. The paper aims rather at presenting an overview of the relevant areas as well as providing links to further reading and related organisations.

The content of the paper is as follows: Section 2 provides a brief overview of the historical development, and Section 3 presents the current status; Section 4 introduces the physical background of utilising the energy in the wind; Section 5 discusses different wind turbine designs; Section 6 deals with the integration of wind energy into the electrical network; Section 7 provides some information about wind energy economics; Section 8 discusses issues related to the installation and the design of wind energy projects; Section 9 presents special system applications, and the conclusions can be found in Section 10.

2. Historical background

The historical development of wind turbine technology is documented in many publications. The following section will therefore provide only a very brief overview of the development. References for this section: [32, pp. 118–130], [29, pp. 9-19], [49, p. 7] and [30,42,21,41,58,54,71,45,47,35,157,53,46].

Table 1
Development of wind turbine size between 1985 and 2000 (source: DEWI [23])[a]

Year	Capacity (kW)	Rotor diameter (m)
1985	50	15
1989	300	30
1992	500	37
1994	600	46
1998	1500	70
2001/2002[a]	4000	88

[a] Figures for the year 2001/2002 are estimated, based on the information published in [10].

2.1. Mechanical power generation

The earliest recorded windmills are vertical-axis mills. These windmills can be described as simple drag devices. They have been used in the Afghan highlands to grind grain since the seventh century BC.

The first details about horizontal-axis windmills are found in historical documents from Persia, Tibet and China at about 1000 AD. This windmill type has a horizontal shaft and blades (or sails) revolving in the vertical plane. From Persia and the Middle-East, the horizontal-axis windmill spread across the Mediterranean countries and central Europe. The first horizontal-axis windmill appeared in England around 1150, in France in 1180, in Flanders in 1190, in Germany in 1222 and in Denmark in 1259 AD. This fast development was most likely influenced by the Crusaders, taking the knowledge about windmills from Persia to many places in Europe.

In Europe, windmill performance was constantly improved between the 12th and 19th centuries. By the end of the 19th century, the typical European windmill used a rotor, 25 m in diameter and the stocks reached up to 30 m. Windmills were not only used for grinding grain, but also for pumping water to drain lakes and marshes. By 1800, about 20,000 modern European windmills were in operation in France alone. And in the Netherlands, 90% of the power used in the industry was based on wind energy. Industrialisation then led to a gradual decline in windmills, but even in 1904 wind energy provided 11% of the Dutch industry energy requirements and Germany had more than 18,000 units installed.

By the time the European windmills slowly started to disappear, windmills were introduced by settlers in North America. Small windmills for pumping water for livestock became very popular. These windmills, also known as American Windmills, operated fully self-regulated, hence they could be left unattended. The self-regulating mechanism pointed the rotor windward during high wind speeds. The European style windmills usually had to be turned out of the wind or the sailing blades had to be rolled-up during extreme wind speeds, to avoid damage to the windmill. The popularity of windmills in the US reached its peak between 1920 and 1930 with about 600,000 units installed. Various types of American Windmills are still used for agricultural purposes all over the world.

2.2. Electrical power generation

In 1891, the Dane Poul LaCour was the first to build a wind turbine generating electricity. Danish engineers improved the technology during World War I and II and used the technology to overcome energy shortages. The wind turbines built by the Danish company F.L. Smidth in 1941–1942 can be considered a forerunner of modern wind turbine generators. The Smith turbines were the first to use modern airfoils, based on the advancing knowledge of aerodynamics at this time. At the same time, the American Palmer Putnam built a giant wind turbine for the American company Morgan Smith Co., with a diameter of 53 m. Not only was the size of this machine significantly different, but also the design philosophy. The

Danish design was based on an upwind rotor with stall regulation, operating at slow speed. Putnam's design was based on a downwind rotor with a variable pitch regulation. Putnam's turbine, however, was not very successful. It was dismantled in 1945 [32]. See Table 2 for an overview of important historical wind turbines.

After World War II, Johannes Juul developed in Denmark the Danish design philosophy further. His turbine installed in Gedser, Denmark, generated about 2.2 million kWh between 1956 and 1967. At the same time, the German Hütter developed a new approach. His wind turbine comprised two slender fibreglass blades mounted downwind of the tower on a teetering hub. Hütter's turbine became known for its high efficiency [32,24].

Despite the early success of Juul's and Hütter wind turbines, the interest in large-scale wind power generation declined after World War II. Only small-scale wind turbines, for remote area power systems or for battery charging, received some interest. With the oil crises in the beginning of the 1970s, the interest in wind power generation returned. As a result, financial support for research and development of wind energy became available. Countries like Germany, USA or Sweden used this money to develop large-scale wind turbine prototypes in the MW range. Many of these prototypes, however, did not perform very successfully most of the time (see Table 3), due to various technical problems, e.g. with the pitch mechanisms.

Nevertheless, due to special government support schemes in certain countries, e.g. Denmark, further development in the field of wind energy utilisation took place. The single most important scheme was the Public Utility Regulatory Policies Act (PURPA), passed by the US Congress in November 1978. With this Act, President Carter and the US Congress aimed at an increase of domestic energy conservation and efficiency, and thereby decreasing the nation's dependence on foreign oil. PURPA, combined with special tax credits for renewable energy systems, led to the first wind energy boom in history. Along the

Table 2
Historical wind turbines (source: Gipe [32, p. 78])

Turbine, country	Diameter (m)	Swept area (m^2)	Power (kW)	Specific power (kW/m^2)	Number of blades	Tower height (m)	Date in service
Poul LaCour, DK	23	408	18	0.04	4	–	1891
Smith-Putnam, US	53	2231	1250	0.56	2	34	1941
F. L. Smidth, DK	17	237	50	0.21	3	24	1941
F. L. Smidth, DK	24	456	70	0.15	3	24	1942
Gedser, DK	24	452	200	0.44	3	25	1957
Hütter, Germany	34	908	100	0.11	2	22	1958

mountain passes east of San Francisco and northeast of Los Angeles, huge wind farms were installed. The first of these wind farms consisted mainly of 50 kW wind turbines. Over the years, the typical wind turbine size increased to about 200 kW at the end of the 1980s. Most wind turbines were imported from Denmark, where companies had further developed Poul LaCour's and Johannes Juul's design philosophy of upwind wind turbines with stall regulation. At the end of the 1980s, about 15,000 wind turbines with a capacity of almost 1500 MW were installed in California.

At this time, financial support for wind energy slowed down in the USA, but picked up in Europe and later in India. In the 1990s, the European support scheme was mainly based on fixed feed-in tariffs for renewable power generation. The Indian approach was mainly based on tax deduction for wind energy investments. These support schemes led to a fast increase of wind turbine installations in some European countries, particularly in Germany, as well as in India.

Parallel to the development of the market size, the technology was also developed further. By the end of the 20th century, 20 years after the unsuccessful worldwide testing of megawatt wind turbines, the 1.5 MW wind turbines have become the technical state-of-the-art.

3. Current status

The following Section will provide a brief overview of the wind energy status

Table 3
Performance of the first large-scale demonstration wind turbines (source: Gipe [32, p. 104])

Turbine, country	Diameter (m)	Swept area (m)	Capacity (MW)	Operating hours	Generated (GWh)	Period
Mod-1, US	60	2827	2	–	–	79–83
Growian, D	100	7854	3	420	–	81–87
Smith–Putnam, US	53	2236	1.25	695	0.2	41–45
WTS-4, US	78	4778	4	7200	16	82–94
Nibe A, DK	40	1257	0.63	8414	2	79–93
WEG LS-1, GB	60	2827	3	8441	6	87–92
Mod-2, US	91	6504	2.5	8658	15	82–88
Näsudden I, S	75	4418	2	11,400	13	83–88
Mod-OA, US	38	1141	0.2	13,045	1	77–82
Tjæcreborg, DK	61	2922	2	14,175	10	88–93
École, CD	64	4000	3.6	19,000	12	87–93
Mod-5B, US	98	7466	3.2	20,561	27	87–92
Maglarp WTS-3, S	78	4778	3	26,159	34	82–92
Nibe B, DK	40	1257	0.63	29,400	8	80–93
Tvind, DK	54	2290	2	50,000	14	78–93

around the world at the end of the 20th century. Furthermore, major wind energy support schemes will be presented. The overview is divided into grid-connected wind power generation and stand-alone systems. Finally, the overall potential of wind energy will be discussed.

References for this Section: Wind energy statistics are regularly published by various organisations. Regional or countrywide statistics are often compiled and published by the corresponding wind energy association (see Section 11.1). Also the *German Wind Energy Institute* as well as the *International Economic Platform for Renewable Energies* regularly publish worldwide statistics (see Section 11.2 for contact details). Regularly updated worldwide statistics are published by *Windpower Monthly* [10] in the January, April, July as well as in the October editions. The Danish wind energy consultant *BTM* also publishes an annual wind energy development status report with worldwide statistics and forecasts. *Wind Force 10* by the *European Wind Energy Association* [94] provides also a very good overview of the current status as well as an interesting future scenario on how to meet 10% of the world's electricity demand with wind power by the year 2020.

3.1. Overview of grid-connected wind power generation

Wind energy was the fastest growing energy technology in the 1990s, in terms of percentage of yearly growth of installed capacity per technology source. The growth of wind energy, however, is not evenly distributed around the world (see Table 4). By the end of 1999, around 69% of the worldwide wind energy capacity was installed in Europe, a further 19% in North America and 10% in Asia and the Pacific.

3.1.1. Europe

Between the end of 1995 and the end of 1999, around 75% of all new grid-connected wind turbines worldwide were installed in Europe (see Tables 4 and 5). The main impetus for this development was the creation of *fixed feed-in tariffs*. Such feed-in tariffs are defined by the governments as the price per kWh that the

Table 4
Operational wind power capacity worldwide (source: January ed. 1997, 1998 and 1999 as well as April ed. 2000 of [10])

Region	Installed capacity (MW)				
	End-1995	End-1996	End-1997	End-1998	End-1999
Europe	2518	3216	4766	6469	9307
North America	1676	1681	1611	2010	2619
South and Central America	11	32	38	52	87
Asia and Pacific	626	897	1149	1257	1403
Middle-East and Africa	13	13	24	26	39
Total worldwide	4844	5839	7588	9814	13455

local distribution company has to pay for local renewable power generation fed into the local distribution grid (for overview of tariffs, see [26]). Fixed feed-in tariffs reduce the risk of changing electricity prices and therefore provide a long-term secure income to investors. Feed-in tariffs, for instance, exist in Germany and Spain.

In England, Scotland as well as Ireland *bidding processes* are used. Thereby, potential developers of renewable energy projects are invited to submit offers for building new projects. Developers bid under different technology brands, e.g. wind, solar, for a feed-in tariff or for the amount of financial incentives to be paid for each kWh fed into the grid by renewable energy systems. The best bidder(s) will be awarded their bid feed-in tariff for a predefined period [51,137].

A new renewable energy policy was introduced in the Netherlands in February, 1998. The approach is based on *Fixed Quotas Combined with Green Certificate Trading*. Thereby, the government introduced fixed quotas for utilities regarding the amount of renewable energy per year they have to sell via their network. On

Table 5
Operational wind power capacity in Europe (source: January ed. 1997 and April ed. 2000 of [10])

Country	Installed capacity (MW)	
	End-1995	End-1999
Germany	1136	4445
Denmark	619	1742
Spain	145	1530
Netherlands	236	410
UK	200	356
Sweden	67	220
Italy	25	211
Greece	28	87
Ireland	7	73
Portugal	13	60
Austria	3	42
Finland	7	38
France	7	23
Norway	4	13
Luxembourg	0	10
Belgium	0	9
Turkey	0	9
Czech Republic	7	7
Poland	1	7
Russia	5	5
Ukraine	1	5
Switzerland	0	3
Latvia	0	1
Romania	0	1
Total	2518	9307

the other hand, producers of renewable energy receive a certificate for a certain amount of energy fed into the grid. The utilities have to buy these certificates to show that they have fulfilled their obligation. Similar schemes are under discussion in other European countries, e.g. Denmark [62].

No detailed data are available regarding the average size of the wind turbines installed in Europe. Table 6 presents the development of the average size of new wind turbine installations in Germany.

The average size of the yearly installed wind turbines in Germany increased from 143 kW in 1989 to 935 kW in 1999. In the first half of 1999, 57% of all new installations in Germany used large wind turbines (rotor diameter > 48.1 m). By June 1999, 603 MW turbines (capacity $\geq$ 1 MW) were installed in Germany. This represents more than 80% of the worldwide installed megawatt turbines. Due to the infrastructure required for the road transport and installation on site, e.g. cranes, megawatt wind turbines are seldom used outside Germany and Denmark. The 500–800 kW range is predominant regarding installation in other European countries.

The first offshore projects have materialised in Denmark, the Netherlands and Sweden (see Table 7). Further offshore projects are planned particularly in Denmark (DK), but also in Sweden (SE), Germany (DE), the Netherlands (NL) and England (UK). Onshore, a significant increase in wind energy development is expected to take place in the near future in Spain, Turkey and Greece (see various editions of [10]).

3.1.2. North America

After the boom in California during the mid-1980s, development slowed down significantly in North America. In the middle of the 1990s, the dismantling of old wind farms sometimes exceeded the installation of new wind turbines, which led to a reduction in installed capacity.

Table 6
Average size of yearly new installed wind capacity in Germany (in kW) (source: German Wind Energy Institute)

Year	Average size of yearly new installed capacity in Germany (kW)
1988	66.9
1989	143.4
1990	164.3
1991	168.8
1992	178.6
1993	255.8
1994	370.6
1995	472.2
1996	530.5
1997	628.9
1998	785.6
1999	935.5

Table 7
Offshore wind energy projects (source: [83], p. 26)

Name	Year	Capacity (MW)	Wind speed at hub (m/s)	Hub height (m)	Distance from shore (km)	Water depth (m)	Speculated cost (ECU/kWh)
Vindeby, Baltic Sea, DK	1991	11×0.45	7.5	37.5	1.5	3–5	2150
Lely, Ijsselmeer, NL	1994	4×0.5	7.7	41.5	1	5–10	1700
Tunø Knob, Baltic Sea, DK	1995	10×0.5	~ 7.5	43	6	3–5	2200
Bockstigen, Baltic Sea, SE	1997	5×0.55	8	41.5	4	6	1500

In 1998, a second boom started in the USA. This time, wind project developers aimed at installing projects before the federal Production Tax Credit (PTC) expired on June 30, 1999. The PTC added $ 0.016–0.017/kWh to wind power projects for the first ten years of a wind plant's life. Between the middle of 1998 and June 30, 1999, the final day of PTC, more than 800 MW of new wind power generation was installed in the USA, which includes between 120 and 250 MW of 'repowering' development at several California wind farms. Apart from California, major projects were carried out in the states of Minnesota, Oregon, Wyoming and Iowa. First large-scale projects have also been installed in Canada (see Tables 8 and 9).

The typical wind turbine size installed in North America at the end of the 1990s was between 500 and 750 kW. The first megawatt turbines were also installed in 1999. In comparison to Europe, however, the overall size of wind farm projects is usually larger. Typical projects in North America are larger than 50 MW, with some projects of up to 120 MW, while in Europe the projects are usually between 20 and 50 MW. The reason for this is the limited space in Europe, due to the high population density in Central Europe. These limitations led to offshore developments in Europe. In North America, offshore projects are not a major topic.

The major driver for further wind energy development in several states in the US are fixed quotas combined with green certificate trading, known in the US as Renewable Portfolio Standard (RPS). The certificates are called Renewable Energy Credits (RECs). The Connecticut RPS will be introduced from July 1, 2000. The quota is set at 0.5%. This percentage of the state's electricity has to come from solar, wind, sustainable biomass, landfill gas, or fuel cells. The level will increase to 1% by July 2002, then to 3% by July 2006, and to 6% by July 2009. Other drivers will be financial incentives, e.g. offered by the California Energy Commission (CEC), as well as green pricing programs. Green pricing is a marketing program offered by utilities to provide choices for electricity customers to purchase power from environmentally preferred sources. Customers thereby agree to pay higher tariffs for 'Green Electricity' and the utilities guarantee to produce the corresponding amount of electricity by using 'Green Energy Sources', e.g. wind energy.

Table 8
Operational wind power capacity in North America (source: see Table 2.)

Country	Installed capacity (MW)	
	End-1995	End-1999
USA	1655	2492
Canada	21	127
Total	1676	2619

Table 9
Operational wind power capacity in the USA by the end of 1999 (source: April ed. 2000 of [10])

State	Installed capacity (MW)
California	1620
Minnesota	273
Iowa	252
Texas	189
Wyoming	72
Oregon	25
Wisconsin	21
Colorado	16
Hawaii	11
Vermont	6
Nebraska	2
Alaska	1
Massachusetts	1
Michigan	1
New York	1
New Mexico	1
Total	2492

3.1.3. South and Central America

Despite large wind energy resources in many regions of South and Central America, the development of wind energy is very slow. This is due to the lack of a sufficient wind energy policy as well as due to low electricity prices. Many wind projects in South America have been financially supported by international aid programs. Argentina, however, introduced a new policy at the end of 1998, which offers financial support to wind energy generation. In Brazil, some regional governments and utilities have started to offer higher feed-in tariffs for wind power (source: [104]).

The typical size of existing wind turbines is around 300 kW. Larger wind turbines are difficult to install, due to infrastructural limitations for larger

Table 10
Operational wind power capacity in South and Central America (source: January ed. 1997 and April ed. 2000 of [10])

Country	Installed capacity (MW)	
	End-1995	End-1999
Costa Rica	0	46
Argentina	3	14
Brazil	2	20
Caribbean	4	4
Mexico	2	3
Total	11	87

equipment, e.g. cranes. Offshore wind projects are not planned, but further small to medium-size (≤ 30 MW) projects are under development onshore (see Table 10).

3.1.4. Asia and Pacific

India achieved an impressive growth in wind turbine installation in the middle of the 1990s, the 'Indian Boom'. In 1992–1993, the Indian Government started to offer special incentives for renewable energy investments, e.g. a minimum purchase rate was guaranteed as well as a 100% tax depreciation was allowed in the first year of the project. Furthermore, a 'power banking' system was introduced, which allows electricity producers to 'bank' their power with the utility and avoid being cut off during times of load shedding. Power can be banked for up to 1 year. In addition, some Indian States have introduced further incentives, e.g. investment subsidies. This policy led to a fast development of new installations between 1993 and 1997. Then the development slowed down, due to uncertainties regarding the future of the incentives (see various editions of [10]).

The wind energy development in China is predominately driven by international aid programs, despite some government programmes to promote wind energy, e.g. the 'Ride-the-Wind' programme of the State Planning Commission. Between 1999 and 2004, the World Bank plans to support five wind projects with a total installed capacity of 190 MW (source: [104]).

In Japan, demonstration projects testing different wind turbine technologies dominated the development. At the end of the 1990s, the first commercial wind energy projects started operations on the islands of Hokkaido as well as Okinawa. At the same time, wind energy projects also materialised in New Zealand and Australia. The main driver for wind energy development in Australia are green pricing programs (see Table 11).

In China and India, the typical wind turbine size is around 300 kW, however, some 500–600 kW wind turbines have also been installed. In Australia, Japan and New Zealand, the 500–600 range is predominant.

Table 11
Operational wind power capacity in Asia and Pacific (source: January ed. 1997 and April ed. 2000 of [10])

Country	Installed capacity (MW)	
	End-1995	End-1999
India	565	1095
China	44	182
Sri Lanka	0	3
South Korea	0	7
Japan	5	68
New Zealand	2	37
Australia	10	11
Total	626	1403

3.1.5. Middle-East and Africa

The wind energy development in Africa is very slow. Most projects require financial support by international aid organisations, as only limited regional support exists. Projects are planned in Egypt, where the government agency for New and Renewable Energy Authority (NREA) would like to build a 600 MW project near the city of Zafarana. Further projects are planned in Morocco (250 MW) as well as in Jordan (25 MW) ([104] and various editions of [10]). The typical wind turbine size used in this region is around 300 kW, but plans exist to use 500–600 kW in future projects (see Table 12).

3.2. Overview of stand-alone generation

Stand-alone systems are usually used to power remote houses or remote technical applications, for example, for telecommunication systems. The wind turbines used for these applications can vary between a few watts and 50 kW. For village or rural electrification systems, wind turbines of up to 300 kW are utilised in combination with a diesel generator and sometimes a battery system. Stand-alone wind turbine systems are also used worldwide to provide mechanical power for pumping drinking and irrigation water or for pumping oil.

Details regarding the worldwide installed capacity of small-scale or stand-alone wind turbines are not available. Regional data are also limited. China, for example, claims to have installed more than 110,000 small turbines (50–200 W). These turbines are mainly used to provide power to nomadic herdsman or farms [32].

Experts predict that the demand for stand-alone systems will grow significantly in the near future. This growth will be driven by the set-up of rural electrification programs in many parts of the world. In Brazil, Mexico, Indonesia, Philippines and South Africa such programs are supported by local utilities. In Indonesia, China, Russia, Mexico, Mauritania and Argentina, similar programs are

Table 12
Operational wind power capacity in Middle-East and Africa (source: January ed. 1997 and April ed. 2000 of [10])

Country region	Installed capacity (MW)	
	End-1995	End-1999
Iran	1	11
Israel	6	8
Egypt	5	15
Jordan	1	2
Rest of Africa	0	3
Total	13	39

supported by international aid programs and the World Bank is financing a program in Brazil [120,31,34].

3.3. Wind energy potential

Often wind energy is discussed in the context of the theoretically available potential. Wind energy potential studies show that the worldwide wind resources are abundant [170,36,94]. Matthies and Garrad, [133], for example, found that the useful offshore potential in European waters alone accounts for around 2500 TWh/year [93]. This is about 85% of the electricity consumption in Europe in 1997 (see also [118]).

The results of wind energy resource studies depend on quality of the available wind energy data as well as on the assumptions about technology and available space. Therefore, such studies can only provide an approximation of the overall wind energy potential. Furthermore, it is important to consider that the wind energy potential can vary significantly for different regions (see also Section 12.2).

4. The basics

The source of wind energy as well as the physical limitations in harvesting this natural resource is discussed next. In addition, a brief overview of the different wind turbine design principles is given.

4.1. The wind

Air masses move because of different thermal conditions of the masses. This motion of the air masses can be found as a global phenomenon, i.e. jet stream, as well as a regional phenomenon. The regional phenomenon is determined by orographic conditions, e.g. the surface structure of the area as well as by global phenomena.Wind turbines utilise the wind energy near the ground. The wind conditions in this area, known as boundary layer, are influenced by the energy transferred from the undisturbed high-energy stream of the geostrophic wind to the layers below as well as by regional conditions. Due to the roughness of the ground, the wind stream near the ground is turbulent.

The wind speed changes with height and the wind speed share depends on the local conditions. There is also a wind direction share over height. Wind turbines therefore experience a wind speed share as well as wind direction share across the rotor, which result in different loads across the rotor.

As most wind energy textbooks describe the known knowledge regarding the wind speed share and wind direction share within the atmospheric boundary layer in more detail, see e.g. [29,30,60], no further details will be given. For a detailed discussion of wind power meteorology, see [145,144,122]. It is, however, important to mention that most textbooks only cover the behaviour of the wind over flat,

uniform terrain. The analysis of the wind share over complex terrain is discussed in more detail, for example, in [129,43,142].

Another important issue is the long-term variations of the wind resources. Different studies regarding this issue have been conducted (see [145, p. 33] and [55,161]). Based on these studies, Petersen et al. estimate that the variation of the mean power output from a 20-year period to the next has a standard deviation of 10% or less. Hence, the uncertainty of the wind resource is not large over the lifetime of a wind turbine, which is an important factor for an economic evaluation of a wind turbine. In many locations in the world, hydropower generation faces a higher uncertainty regarding the availability of water, than wind power [42].

4.2. The physics

The power of the wind that flows at speed V through an area A is ρAV, therefore

Power wind $= \frac{1}{2}A\ V^3$ (W)
ρ = air density (kg/ m^3)
V = wind speed (m/s)

The power in the wind is proportional to the air density ρ, the intercepting area A and the velocity V to the third power. The air density is a function of air pressure and air temperature, which both are functions of the height above sea level.

$\rho(z) = P_0/(R \cdot T)\exp(-g \cdot z/(RT))$
$\rho(z)$ = air density as a function of altitude (kg/m^3)
P_0 = standard sea level atmospheric pressure (kg/m^3)
R = specific gas constant for air (J/K mol)
T = temperature (K)
g = gravity constant (m/s^2)
z = altitude above sea level (m)

The power in the wind is the total available energy per time unit. The power in the wind is converted into the mechanical–rotational energy of the wind turbine rotor, which results in a reduced speed of the air mass. The power in the wind cannot be extracted completely by a wind turbine, as the air mass would be stopped completely in the intercepting rotor area. This would cause a 'congestion' of the cross-sectional area for the following air masses.

The theoretical optimum for utilising the power in the wind by reducing its velocity was first discovered by Betz, in 1926 [22]. According to Betz, the theoretically maximum power that can be extracted from the wind is

$$P_{\mathrm{Betz}} = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \cdot C_{\mathrm{P{\cdot}Betz}} = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \cdot 0.59$$

Hence, even if a power extraction without any losses would be possible, only 59% of the wind power could be utilised by a wind turbine. For further details, see wind energy textbooks, e.g. [60,29,30].

Many textbooks, however, do not mention that Betz did not consider the impact of unavoidable swirl losses. For turbines with a high tip speed ratio, $X > 3$, and an optimum blade geometry, these losses are very low. The tip speed ratio, X, of a rotor is defined as:

$$X = \frac{V_{\mathrm{tip}}}{V_{\mathrm{wind}}} = \frac{\omega R}{V_0}$$

For turbines with a low tip speed ratio, e.g. the American farm windmill with $X \approx 1$, the swirl losses reduce the maximum power coefficient, $C_{\mathrm{P,\ max}}$, to approximately 0.42 [29,30].

4.3. Types of wind turbines

Wind energy conversion systems can be divided into those which depend on aerodynamic drag and those which depend on aerodynamic lift. The early Persian (or Chinese) vertical axis windwheels utilised the drag principle. Drag devises, however, have a very low power coefficient, with a $C_{\mathrm{P,max}}$ of around 0.16 [29,30].

Modern wind turbines are predominantly based on the aerodynamic lift. Lift devices use airfoils (blades) that interact with the incoming wind. The force resulting from the airfoils body intercepting the air flow does not only consist of a drag force component in direction of the flow but also of a force component that is perpendicular to the drag: the lift forces. The lift force is a multiple of the drag force and therefore the relevant driving power of the rotor. By definition, it is perpendicular to the direction of the air flow that is intercepted by the rotor blade, and via the leverage of the rotor, it causes the necessary driving torque [159,29,30,60,32].

Wind turbines using the aerodynamic lift can be further divided according to the orientation of the spin axis into horizontal-axis and vertical-axis type turbines. Vertical-axis turbines, also known as Darrieus after the French engineer who invented it in the 1920s, use vertical, often slightly curved symmetrical airfoils. Darrieus turbines have the advantage that they operate independently of the wind direction and that the gearbox and generating machinery can be placed at ground level. High torque fluctuations with each revolution, no self-starting capability as well as limited options for speed regulations in high winds are, however, the major disadvantages. Vertical-axis turbines were developed and commercially produced in the 1970s until the end of the 1980s. The largest vertical-axis wind turbine was installed in Canada, the ECOLE C with 4200 kW. Since the end of the 1980s, however, the research and development of vertical-axis wind turbines has almost stopped worldwide [29,30,60,32].

The horizontal-axis, or propeller-type, approach currently dominates the wind turbine applications. A horizontal-axis wind turbine consists of a tower and a nacelle that is mounted on the top of a tower. The nacelle contains the generator, gearbox and the rotor. Different mechanisms exist to point the nacelle towards the wind direction or to move the nacelle out of the wind in case of high wind speeds.

On small turbines, the rotor and the nacelle are oriented into the wind with a tail vane. On large turbines, the nacelle with rotor is electrically yawed into or out of the wind, in response to a signal from a wind vane.

Horizontal-axis wind turbines typically use different numbers of blades, depending on the purpose of the wind turbine. Two- or three-bladed turbines are usually used for electricity power generation. Turbines with 20 or more blades are used for mechanical water pumping.

The number of rotor blades is indirectly linked to the tip speed ratio, see Fig. 1. Wind turbines with a high number of blades have a low tip speed ratio but a high starting torque. This high starting torque can be utilised for fully automatically starting water pumping when the wind speed increases. A typical example for such

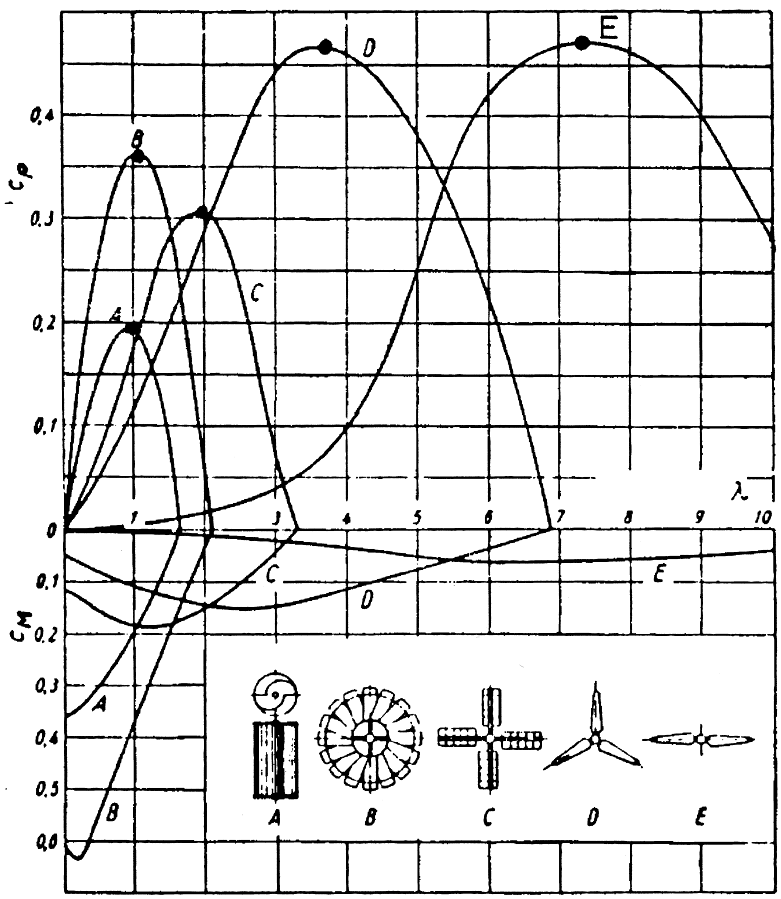


Fig. 1. Power coefficient (C_p) and torque (C_M) of windwheels varying in construction versus tip speed (λ); A, B, C = typical windwheels with a low tip speed ratio; D, E = typical windwheels with a high tip speed ratio (source: [29, p. 163])

an application is the American farm windmill. Wind turbines with only two or three blades have a high tip speed ratio, but only a low starting torque. These turbines might need to be started, if the wind speed reaches the operation range. But a high tip speed ratio allows the use of a smaller and therefore lighter gearbox to achieve the required high speed at the driving shaft of the power generator [166,29,30,60,32].

Apart from the above discussed wind turbine design philosophies, inventors frequently come up with new designs, using some kind of power argumentation, for instance. None of these inventions have given sufficient large-scale performances yet. For the current status of power argumentation wind turbines, see [168,100].

5. Technology

The following Section will provide a more in-depth overview of the technology trends of horizontal-axis, medium to large size grid-connected wind turbines (≥100 kW). This type of wind turbine currently has the largest market share and it is also expected to dominate the development in the near future.

Table 13
Basic design approaches (source: Thresher et al. [166])

A. Turbines designed to withstand high wind loads • optimize for reliability • high solidity, but non-optimum blade pitch • three or more blades • lower rotor tip–speed ratio Precursor: Gedser mill
B. Turbines designed to be compliant and shed loads • optimize for performance • low solidity, optimum blade pitch • one or two blades • higher rotor tip–speed ratio Example: Hütter turbine
C. Turbines designed to manage loads mechanically and/or electrically • optimize for control • mechanical and electrical innovations (flapping or hinged blades, variable speed generators, etc.) • two or three blades • moderate rotor tip–speed ratio Example: Smith–Putnam

5.1. Design approaches

Horizontal-axis wind turbines can be designed in different ways. Thresher et al. [166] distinguish three design philosophies, see Table 13. Modern grid-connected wind turbines usually follow the 'C' approach, as it results in

- better power quality;
- lower tip-speed ratios than approach 'B', hence lower visual disturbances;
- lower material requirements than in approach 'A', as the structure does not need to withstand high wind loads, hence lower cost.

Different companies also investigate combinations of the different approaches. However, the 'C' approach currently dominates the commercial market. See [166] for more details.

Each of the design approaches leave a high degree of freedom regarding certain design details. For example, depending on the wind environment, different aerodynamic rotor diameters can be utilised. On high wind speed sites, usually smaller rotor diameters are used with an aerodynamic profile that will reach the maximum efficiency between 14 and 16 m/s. For low-wind sites, larger rotors will be used, but with an aerodynamic profile that will reach maximum efficiency already between 12 and 14 m/s. In both cases, the aim is to maximise the yearly energy harvest. In addition, wind turbine manufactures have to consider the overall cost, including the maintenance cost over the lifetime of the wind turbine.

The most important design variables are discussed next, e.g. the number of blades, power control system and generation/transmission system. For further details regarding the design of wind turbines, see [147,166,29,30,39,40,32] and [49 pp. 26–47] for an overview of related articles.

5.2. Two- or three-bladed wind turbines

Currently, three-bladed wind turbines dominate the market for grid-connected, horizontal-axis wind turbines. Two-bladed wind turbines, however, have the advantage that the tower top weight is lighter and, therefore, the whole supporting structure can be built lighter, and thereby very likely cost will be lower.

Three-bladed wind turbines have the advantage that the rotor moment of inertia is easier to understand and, therefore, often better to handle than the rotor moment of inertia of a two-bladed turbine [166]. Furthermore, three-bladed wind turbines are often attributed 'better' visual aesthetics and a lower noise level than two-bladed wind turbines. Both aspects are important considerations for wind turbine utilisation in highly populated areas, e.g. the European coastal areas.

5.3. Power control

Wind turbines reach the highest efficiency at the designed wind speed, which is usually between 12 and 16 m/s. At this wind speed, the power output reaches its

rated capacity. Above this wind speed, the power output of the rotor must be limited to keep the power output close to rated capacity and to reduce thereby the driving forces on the individual rotor blade as well as the load on the whole wind turbine structure. Three options for the power output control are currently used:

Stall regulation: This principle requires a *constant* rotational speed, i.e. independent of the wind speed. A constant rotational speed can be achieved with a grid-connected induction generator. Due to the airfoil profile, the air stream conditions at the rotor blade change in a way that the air stream creates turbulence in high wind speed conditions, on the side of the rotor blade that is not facing the wind. This effect is known as the stall effect (see also Fig. 2).

The effect results in a reduction of the aerodynamic forces and, subsequently, of the power output of the rotor. The stall effect is a complicated dynamic process. It is difficult to calculate the stall effect exactly for unsteady wind conditions. Therefore, the stall effect was for a long time considered to be difficult to use for large wind turbines. However, due to the experience with smaller and medium-sized turbines, blade designers have learned to calculate the stall phenomenon more reliably. Today, even some manufacturers of megawatt turbines use stall-regulation, but the first prototypes of multi-megawatt wind turbines still avoid stall regulation (see overview of wind turbines in Section 5.6). Fig. 3 shows a typical power output chart of a turbine using stall control.

Pitch regulation: By pitching the rotor blades around their longitudinal axis, the relative wind conditions and, subsequently, the aerodynamic forces are affected in a way so that the power output of the rotor remains constant after rated power is reached. The pitching system in medium and large grid-connected wind turbines is usually based on a hydraulic system, controlled by a computer system. Some manufacturers also use electronically controlled electric motors for pitching the blades. This control system must be able to adjust the pitch of the blades by a

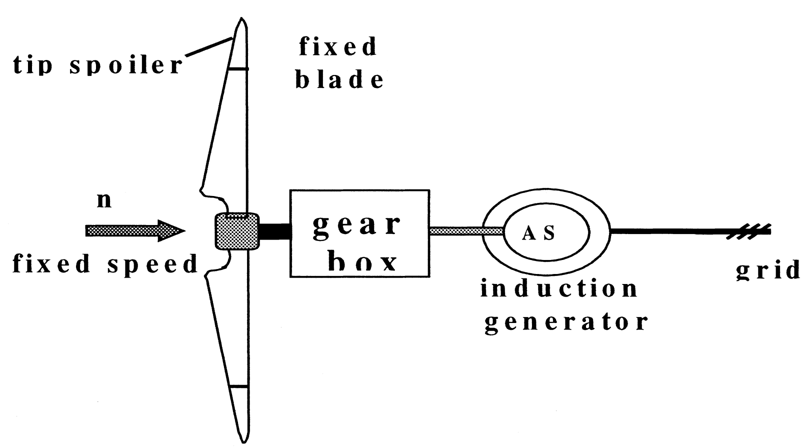


Fig. 2. Danish type of wind turbine with induction generator (constant rotational speed).

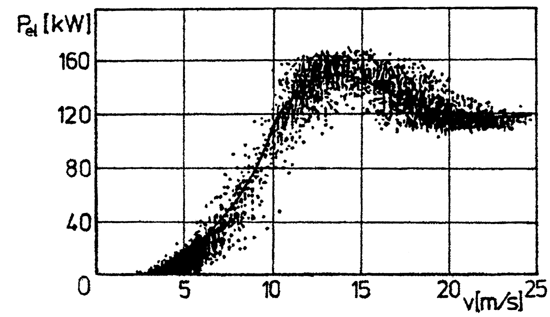


Fig. 3. Typical power output chart of a turbine using stall control (BONUS 150 kW, $D = 23$ m, 10 min means are shown (source: [29, p. 75]).

fraction of a degree at a time, corresponding to a change in the wind speed, in order to maintain a constant power output (see Fig. 4).

The thrust of the rotor on the tower and foundation is substantially lower for pitch-controlled turbines than for stall-regulated turbines. In principle, this allows for a reduction of material and weight, in the primary structure. Pitch-controlled turbines achieve a better yield at low-wind sites than stall-controlled turbines, as the rotor blades can constantly be kept at optimum angle even at low wind speeds.

Stall-controlled turbines have to be shut down once a certain wind speed is reached, whereas pitch-controlled turbines can gradually change to a spinning mode as the rotor operates in a no-load mode, i.e. it idles, at the maximum pitch angle. An advantage of stall-regulated turbines consists in that in high winds — when the stall effect becomes effective — the wind oscillations are converted into power oscillations that are smaller than those of pitch-

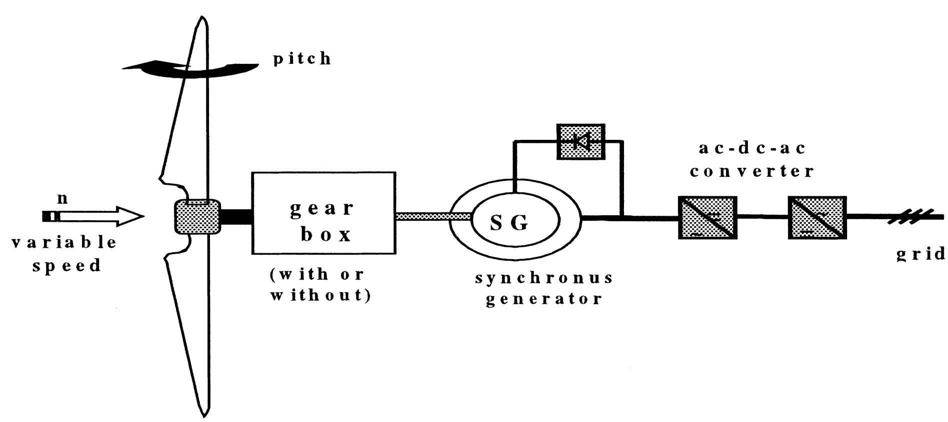


Fig. 4. Pitch-controlled variable speed wind turbine with synchronous generator and ac–dc–ac power conversion.

controlled turbines in a corresponding regulated mode. Particularly, fixed-speed pitch-controlled turbines with a grid-connected induction generator have to react very quickly to gusty winds. This is only possible within certain limits, otherwise huge inertia loads counteracting the pitching movement will be caused. Fig. 5 shows the output characteristics typical of a wind turbine using pitch control.

Active stall regulation: This regulation approach is a combination between pitch and stall. At low wind speeds, blades are pitched like in a pitch-controlled wind turbine, in order to achieve a higher efficiency and to guarantee a reasonably large torque to achieve a turning force. When the wind turbine reaches rated capacity, the active stall-regulated turbine will pitch its blades in the opposite direction than a pitch-controlled machine does. This movement will increase the angle of attack of the rotor blades in order to make the blades go into a deeper stall. It is argued that active stall achieves a smoother limiting of power output, similar to that of pitch-controlled turbines without their 'nervous' regulating characteristics. It preserves, however, the advantage of pitch-controlled turbines to turn the blade into the low-load 'feathering position', hence thrust on the turbine structure is lower than on a stall-regulated turbine.

Other control methods are ailerons as well as to yaw the rotor partly out of the wind in order to decrease power. Ailerons are flaps in the blades, just like the flaps in aircraft wings; however, they are not used by the wind energy industry. Yawing is only used for small wind turbines (~5 kW or less), as the stress on the entire structure is very difficult to handle with larger wind turbines.

If the wind speed reaches cut-out wind speed (usually between 20 and 30 m/s), the wind turbine shuts off and the entire rotor is turned out of the wind to protect the overall turbine structure. Because of this procedure, possible energy that could have been harvested will be lost. However, the total value of the lost energy over the lifetime of the wind turbine will usually be smaller than the investments that will be avoided by limiting the strength of the turbine to the cut-out speed.

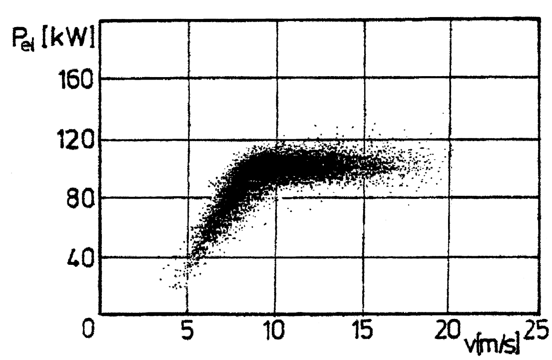


Fig. 5. Output characteristics typical of a wind turbine using pitch control (DEBRA 100 kW, $D = 25$ m [21], its mean values are shown) (source: [29, p. 76]).

Limiting the strength of the turbine requires emergency or overspeed control systems to protect the wind turbine in case of a failure of the brakes. Typical overspeed control systems are tip brakes or pitchable tips included in the rotor blades [32].

For high wind speed sites, the cut-out wind speed and the setpoint for starting up the wind turbine again after the wind turbine was stopped and turned out of the wind, can have a significant impact on the energy yield. Typically, a wind turbine shuts down every time the 10-min wind speed average is above the cut-out wind speed, e.g. 25 m/s. The setpoint for starting up the wind turbine varies widely throughout the industry. Often, wind turbines start up operation when the 10-min average wind speed drops below 20 m/s. However, the setpoint can vary between 14 and 24 m/s, depending on the wind turbine type. Low setpoints for resuming the wind power production have a negative impact on the energy production. The above phenomenon is described in specialist publications as hysteresis effect or hysteresis loop [169].

Details of the rotor aerodynamics are not covered in this paper, as a review of the current status of rotor aerodynamics is available in [159]. It is, however, important to mention that most modern rotor blades of large wind turbines are made of glass fibre reinforced plastics (GRP), i.e. glass fibre reinforced polyester or epoxy, and are equipped with a lightning protection system.

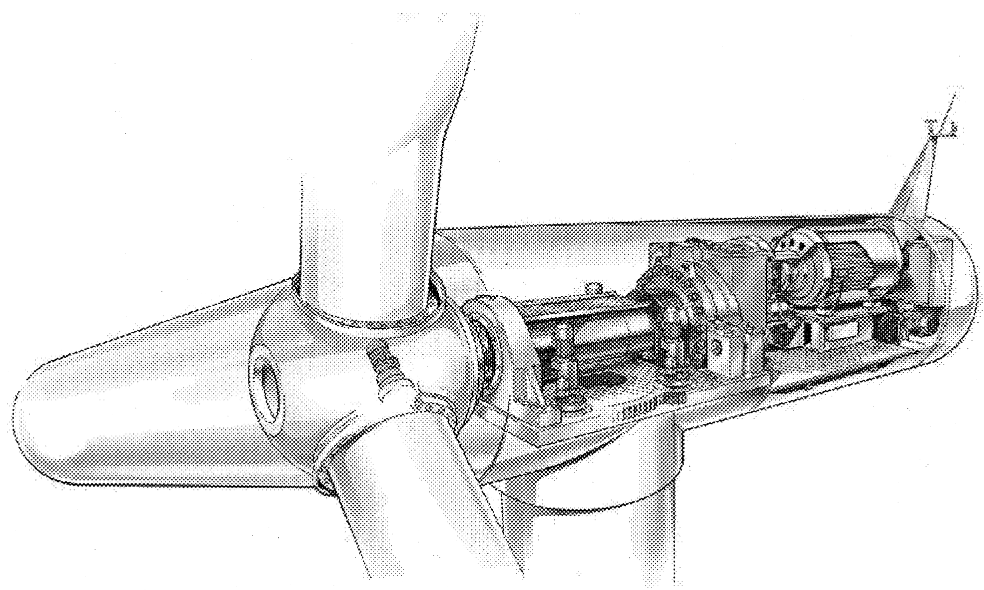


Fig. 6. Nacelle Bonus 1 MW (courtesy of BONUS Energy A/S, Denmark).

5.4. Transmission and generator

The power generated by the rotor blades is transmitted to the generator by a transmission system. The transmission system consists of the rotor shaft with bearing, break(s), an optional gearbox, as well as a generator and optional clutches. In real life, there is a large variety regarding the placement of these components. See Figs. 6 and 7 and [29,30] for a detailed discussion of the placement.

Most wind turbine manufacturers use six-pole induction (asynchronous) generators, while others use directly driven synchronous generators. In the power industry, in general, induction generators are not very common for power production, but induction motors are used worldwide. The power generation industry almost exclusively uses large synchronous generators, as they have the advantage of a variable reactive power production, i.e. voltage control.

Synchronous generators of 500 kW to 2 MW are significantly more expensive than induction generators with a similar size. In addition, directly grid-connected synchronous generators have the disadvantage that the rotational speed is fixed by the grid frequency and the number of pairs of poles of the generator. Hence, fluctuations in the rotor power output, e.g. due to gusts, lead to a high torque on the drivetrain as well as high power output fluctuations, unless other means, e.g. softer towers, are used to reduce the impact of gusts. Therefore, directly grid-

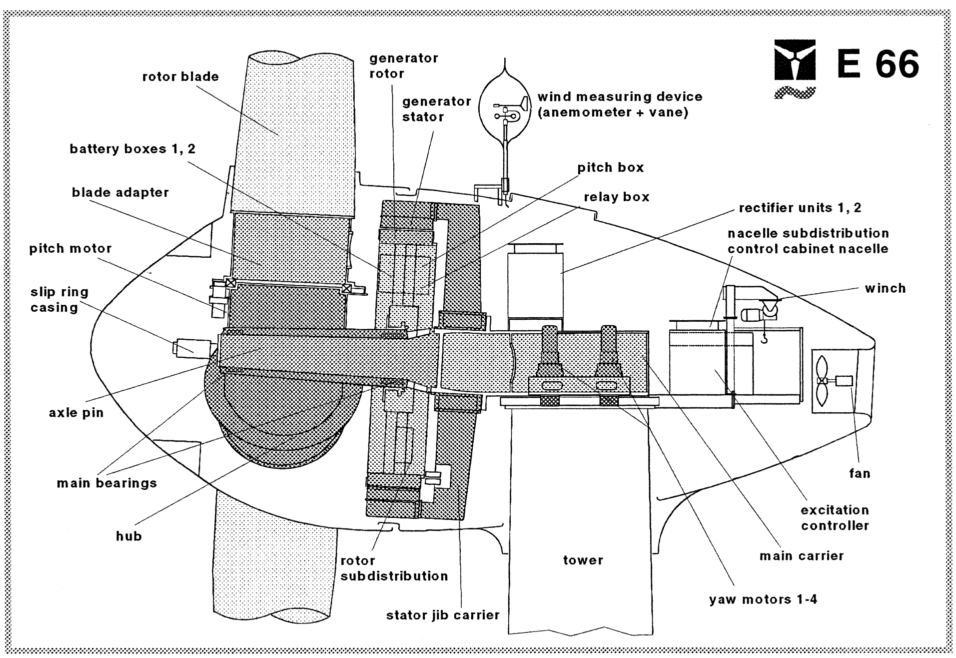


Fig. 7. Nacelle Enercon 1.5 MW (courtesy of Enercon, Germany)

connected synchronous generators are usually not used for grid-connected wind turbines. They are applied in stand-alone systems sometimes, where the synchronous generator can be used for reactive power control in the isolated network.

An option for the utilisation of synchronous generators for wind turbines is the decoupling of the electric connection between the generator and the grid through an intermediate circuit. This intermediate circuit is connected to a three-phase inverter that feeds the grid with its given voltage and frequency. Today, pulse-width modulated (PWM) inverters are commonly used. For further discussions of details regarding the coupling of variable speed generators to the network, see [39,40].

The decoupling of grid and the rotor/generator allows a variable speed operation of the rotor/generator system. Fluctuations in the rotor output lead to a speed-up or slow-down of the rotor/generator. This results in a lower torque on the drivetrain as well as a reduction of power output fluctuations. Furthermore, it is important to remember that the maximum power coefficient occurs only at a single tip-speed ratio. Hence, with a fixed-speed operation the maximum power coefficient is only reached at one wind speed. With a variable speed operation, the rotor speed can accelerate and decelerate in accordance with the variations in the wind speed in order to maintain the single tip-speed ratio that leads to a maximum power coefficient [166].

The industry uses directly driven variable speed synchronous generators with large-diameter synchronous ring generator (see Fig. 7). The variable, directly driven approach avoids the installation of a gearbox, which is essential for medium and large-scale wind turbines using an induction generator. The gearbox is required to increase the rotational speed from around 20 to 50 revolutions per min (rpm) on the rotor side to, for example, 1200 rpm (for 50 HZ) on the induction generator side. This rotational speed on the induction generator side is necessary to produce power at the required network frequency of 50 Hz (or 60 Hz). The required rpm for the generator depends on the number of pole pairs.

The directly driven synchronous ring generator of the Enercon E40 (500 kW), on the other hand, operates with a variable rotational speed of 18–41 rpm.

Induction generators have a slightly softer connection to the network frequency than synchronous generators, due to a changing slip speed. This softer connection reduces the torque between rotor and generator during gust slightly. However, this almost fixed-speed operation still leads to the problem that overall efficiency during low wind speeds is very low. The traditional Danish approach to overcoming this problem is to use two induction generators, one small and one large one. Today, the same effect is achieved with pole changing machines. With this approach, two rotational speeds are possible. The small induction machine is connected to the grid during low wind speeds. When the wind speed increases, the small generator is switched off and the large generator is switched on. The operating point of the larger generator lies at a higher rotational speed.

To further reduce the load on the wind turbine and to make use of the advantages of variable-speed generation with induction generators, it is reasonable

to further decouple rotor speed and grid frequency. There are various approaches to achieving a variable-speed operation within a certain operational range. Today, dynamic slip control, where the slip can vary between 1 and 10%, and double fed asynchronous generators, are most commonly used by the industry. For an overview of the different approaches see [40, p. 105].

The reactive power requirements are the disadvantage of induction generators. As a reactive power flow to the network is usually not desired by the network operators, turbines with induction generators are usually equipped with capacitors. These capacitors usually compensate the reactive power demand of the induction generators. Another setback of induction generators is the high current during the start-up of the generator, due to the required magnetising of the core. Controlling the voltage applied to the stator during the start-up and thereby limiting the current can solve the problem.

A description of synchronous and induction generators can be found in many standard textbooks. Heier [39,40] provides a good overview regarding the different generator technologies currently used by the wind industry as well as future options for the design of wind turbine generators, e.g. permanently excited synchronous generators. Such generators have been tested in demonstration projects but are currently not applied in medium or large-scale wind turbines. They are, however, quite common in small-scale (10 kW or less) wind turbines.

The evaluation of the different wind turbine designs is difficult, even with production data, as the local wind resources can vary significantly between different locations. However, production data of existing wind turbines are an important source of information regarding wind turbine performance at particular locations. Wind turbine production data are often published by wind energy associations (see Section 11.1). Good resources regarding wind turbine performance data are also available in the following publications and research projects [11,44,15,90]

5.5. Technology standards

Wind energy standards become more and more important for ensuring a certain design quality of wind turbines or for defining performance testing, acoustic and meteorological measurements at a potential wind turbine site.

Many countries, e.g. Germany, Denmark, USA and India, have developed their own set of wind energy standards. However, the trend is to internationally harmonise the worldwide wind energy standards. More information about the international activities towards a standard can be obtained from European Wind Turbine Standards (EWTS) Project [1] as well as from the American Wind Energy Association (AWEA), which is recognised by the American National Standards Institute (ANSI) as the only authorised wind energy standard-setting body in the United States [68].

The International Electrotechnical Commission (IEC) in Geneva, has defined and published international standards regarding wind energy technology. See, for example [111–117], or see the IEC webpage [110] for further information.

Particularly interesting is IEC 61400-21, which characterises the relevant power quality parameters for wind turbines. The standards are discussed in detail in [102].

5.6. Wind turbine overview

Tables 14 and 15 provide an overview of representative existing wind turbines as well as large wind turbines currently under development.

6. Network integration

In most parts of the world, wind energy supplies only a fraction of the total power demand. In other regions, for example in northern Germany, Denmark or on the Swedish island of Gotland, wind energy supplies already a significant amount of the total energy demand. In 1998, wind energy supplied around 1.750 GWh out of 12.406 GWh (14.1%) in the German province of Schleswig–Holstein, in Denmark around 1.830 GWh out of 32.500 GWh (5.6%) and 112 GWh out of 900 GWh (12.5%) on Gotland in Sweden.

With increasing wind power penetration, the availability of wind power generation as well as its influence on the network becomes of particular interest. The relevant issues are briefly discussed next.

6.1. Availability

Wind generation has a fluctuating power output, due to the variability of the wind speed. Table 16 lists causes and time scales of wind variations.

The fluctuations in the available wind energy caused by gusts result in power output fluctuations from the wind turbine. Such power fluctuations may affect the power quality of the network. A reduction of short-term power fluctuations can be achieved using variable-speed operated wind turbines as they are able to absorb short-term power variations by the immediate storage of energy in the rotating masses of the drivetrain, hence, a smoother power output is achieved than with strongly grid-coupled turbines [131].

An additional smoothing effect is achieved when a wind farm consists of a large number of wind turbines, short-term fluctuations in the overall output are reduced due to the effect that gusts do not hit all wind turbines at the same time. Under ideal conditions, the variations of power output will drop with $1/\sqrt{n}$, where n is the number of wind generators [155]. For the time range of subseconds, Santjer et al. [155], however, found that the smoothing or compensating between different wind turbines in a wind farm cannot be expected, in general. Particularly during switching, e.g. the start-up of a wind farm, the grid interferences are higher than assumed by the $1/\sqrt{n}$-rule. Stampa [164] even found that wind turbines with directly grid-connected induction generators in a wind farm could fall into synchronism with their rotor azimuth position. This synchronism can cause high

Table 14
Size and weight data for representative turbines. DFAG = double fed asynchronous generator, DD = direct driven, variable speed, electrically excited synchronous generator, VAS = asynchronous generator with variable slip; AS = asynchronous (source: [166,139] and authors)

Type	Control system (P) pitch, (S) stall, (AS) active stall	Rotor diameter (m)	Number of blades	Rated capacity (kW)	Nacelle and rotor weight (kg)	Weight per swept area (kg/m^2)	Generator
Bonus 300 kW	S	31	3	300	14,500	19.2	AS
Bonus 1 MW	AS	54	3	1000	63,000	27.5	AS
Bonus 2 MW	AS	76	3	2000	125,000	27.7	AS
Carter	AS	24	2 (T)	300	4431	10	AS
DeWind D4	P	45.8	3	600	34,000	20.6	DFAG
DeWind D6	P	62	3	1000	65,000	21.5	DFAG
Enercon E-40	P	40	3	500	29,500	23.1	DD
Enercon E-66	P	66	3	1500	99,590	29.1	DD
Lagerwey 18/80	P	18	2 flex	80	3000	11.8	AS
Lagerwey 27/250	P	27	2 flex	250	10,000	17.5	AS
Lagerwey 50/750	P	50.5	3	750	–	–	DD
NEG Micon:							
NM 600/43	S	43	3	600	35,000	24.1	AS
NM 750/48	S	48	3	750	34,000	18.6	AS
NM 1000/60	S	60	3	1000	57,000	20.1	AS
NM 1500C/64	S	64	3	1500	74,000	23.0	AS
Nordic 1000	S	54	2	1000	45,000	19.6	VAS
Nordex N-29	S	29.7	3	250	16,800	24.2	AS
Nordex N-43	S	43	3	600	35,500	24.5	AS
Nordex N-54	S	54	3	1000	69,800	30.5	AS
Nordex N-63	S	63	3	1300	69,400	24.5	AS
Nordex N-80	P	80	3	2500	119,300	23.7	DFAG
Riva Calzaoni M30-52	P	33	1	–	13,500	15.8	AS
Südwind S33	S	33.4	3	350	–	–	AS

Südwind S46/750	P	46	3	750	–	–	DFAG
Tacke TW 600	S	43	3	600	33,000	22.7	AS
Tacke TW 1.5	P	65	3	1500	74,000	22.3	DFAG
Tacke TW 2.0	P	70.5	3	2000	80,000	20.5	DFAG
Vestas V29	P	29	3	225	13,000	19.7	VAS
Vestas V44	P	44	3	600	25,700	16.9	VAS
Vestas V63	P	63.6	3	1500	74,000	23.7	VAS
Vestas V66	P	66	3	1650	78,000	22.8	VAS
Vestas V80	P	80	3	2000	95,000	18.9	VAS
Zond	P	50	3	750	–	–	DFAS

Table 15
Data of large wind turbines currently under development (source: [139])

Type	Country	Control system (P) pitch, (S) stall, (AS) active stall	Rotor diameter (m)	Number of blades	Rated capacity (kW)	(VS) Variable speed, (FS) fixed speed
Enercon E-70	Germany	P	70	3	1800	VS
Zond Z1800	USA	P	80	3	1800	VS
NEG Micon:						
2000/72	Denmark	AS	72	3	2000	FS
2000/78	Denmark	AS	78	3	2000	FS
Wincon 2000	Denmark	AS	70	3	2000	FS
DeWind 90	Germany	P	90	3	2500	VS
Kvarner 3 MW	Sweden	P	86	3	3000	VS
Kvarner 3 MW	Sweden	P	86	3	3500	VS
Enercon E-112	Germany	P	112	3	4000	VS
Multibrid	Germany	S + tips	100	3	5000	VS

Table 16
Causes and time scale of wind variation (source: Davitian [82])

Causes of variation	Time scale of variation
Gusts (turbulence)	Sub-second to second
Diurnal cycle	Daily
Inversion layers	Hours
Changing weather patterns	Hours to days
Seasonal cycle (monsoon)	Seasonal
Annual variation	Years

amplitudes in voltage fluctuations. Both situations can be avoided by co-ordinating the operation of the different wind turbines in a wind farm and by varying the electrical parameters of the wind farm grid.

The medium-term variations (hours) are also very important for network operation, as network operators have to dispatch other generation sources, if the wind energy power output varies strongly.

Fig. 8 is based on the 1997 statistical analysis of 63 wind turbines (total 11.4 MW) installed in the area of Schleswig–Holstein. The figure shows the statistical average probability of a power output change of the total installed wind capacity from the mean power gradient of 1 h (or 4 or 12 h) to the next.

It can be seen, that with a probability of 30% the hourly mean wind power output from one hour to the next will be ±1% of total installed capacity (±4%

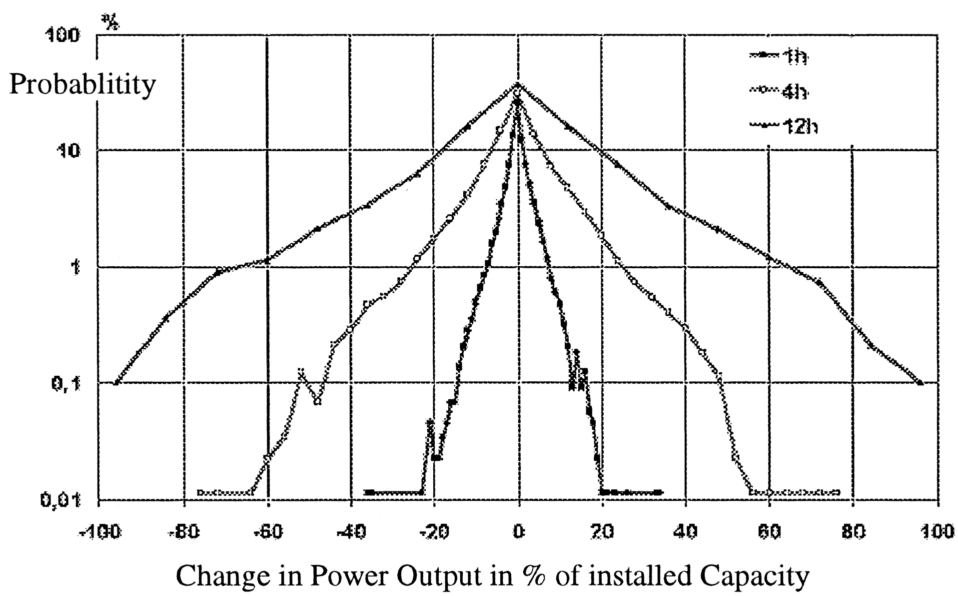


Fig. 8. Power gradient for extended periods (Schleswig–Holstein) (source: ISET [44, p. 50]).

from one 4 hourly mean to the next and ±12% between the 12 hourly mean). The largest change in power output to be expected between hourly mean power output values is about 40% (probability 0.01%) of installed capacity (about 80% between 4 hourly means, and almost 100% between 12 hourly means). A Danish study [79] as well as a Dutch study [37, p. 89], confirmed the relatively large compensation of the power variations between different wind turbines distributed over a larger area. The Danish study, however, emphasised that the variations per minute can still be significant.

Long-term variations in wind speed, between 1 year and the next, are usually quite low, as discussed in Section 4.1.

6.2. Power quality

Wind turbines as well as all other equipment connected to the public grid, affect the quality of the power in the grid. These effects include voltage fluctuations due to power fluctuations and may be flicker effects, voltage asymmetry and harmonics. Detailed discussion of these effects can be found in standard textbooks, e.g. [39,40]. To study the impact of wind turbines on the power network, detailed computer models of wind turbines are used, see e.g. [64–67].

The evaluation of the impact of wind turbines on the power quality is a complex problem, due to the unique design of each distribution network as well as the different types of wind turbines, e.g. variable speed or fixed speed, stall or pitch-regulated. Fixed-speed wind turbines, for example, produce a power pulsation emanating from the wind share over height, and the tower shadow effect. Such a power pulsation will cause voltage fluctuations on the grid, which in turn may cause flicker. Variable-speed as well as limited variable-speed turbines, e.g. with induction generators with variable slip, significantly reduce the power fluctuations due to wind share and tower shadow effect [141].

The start-up of wind turbines is also an important issue. The grid connection during the start-up of stall-regulated fixed-speed wind turbines can cause high inrush currents, as the rotor torque cannot be exactly controlled to meet the required generator torque. Pitch-regulated fixed-speed as well as variable-speed wind turbines are able to achieve a smoother grid connection during start-up [141,131,78].

Another issue is the introduction of harmonics and interharmonics. This issue is not relevant for fixed-speed but for variable-speed wind turbines, as they are equipped with a power converter that can emit harmonics or interharmonics during continuous operation. Line commutated inverters produce harmonics of low orders (250–350 Hz) and force commutated inverters using PWM and IGBT produce harmonics of high orders (≥6 kHz) [78]. Special filters are used to reduce harmonics. To limit the influence of harmonics on the grid power quality, power converters used within wind turbines should perform in accordance with international standards, e.g. IEC 61300-3 and 61000-4-7 [112,111].

The steady-state voltage in a grid system also fluctuates, due to the fluctuations in load. This situation occurs particularly in weak grid systems, e.g. long, low-

loaded, low-voltage transmission lines. The additional connection of wind farms may increase these voltage fluctuations, due to short as well as long-term fluctuations in the power output. However, wind turbines with controllable power factor might also be able to reduce the voltage fluctuations if the power factor of the wind turbine is continuously adjusted according to the voltage fluctuations caused by the system load [63].

And finally, an increase of wind energy penetration might result in new phenomena, e.g. voltage collapse problems. As Denmark wants to increase its wind power penetration to 50% until the year 2030, detailed studies are currently being conducted by Danish network operators, see e.g. [77]. One of the suggested solutions currently discussed is the installation of advanced HVDC technology within the distribution network or as transmission technology between the onshore network and large offshore wind farms, see [20,89].

7. Economics

In the 1990s, the cost for manufacturing wind turbines declined by about 20% every time the number of manufactured wind turbines doubled [163]. Currently, the production of large-scale, grid-connected wind turbines doubles almost every 3 years. Similar cost reductions have been reported for PV solar and biomass, however, these technologies have slightly different doubling cycles. A similar cost reduction was achieved during the first years of oil exploitation about 100 years ago. But the cost reduction for electricity production between 1926 and 1970 in the USA, mainly due to economies of scale, was higher. An average cost reduction of 25% for every doubling of production is reported for this time period [156].

The Danish Energy Agency predicts that a further cost reduction of 50% can be achieved until 2020, and the EU Commission estimates in its White Book that energy cost from wind power will be reduced by at least 30% between 1998 and 2010 [163]. Other authors though, emphasise that the potential for further cost reduction is not unlimited and very difficult to estimate [32].

A general comparison of the electricity production costs, however, is very difficult as production costs vary significantly between countries, due to the availability of resources, different tax structures or other reasons. In addition, market regulations can affect the electricity prices in different countries. The competitive bidding processes for renewable power generation in England and Wales (*The Non-Fossil Fuel Obligation — NFFO*), however, provides a good comparison of power production prices. Within this bidding process, potential project developers for renewable energy projects are invited to bid for building new projects. The developers bid under different technology brands, e.g. wind or solar, for a feed-in tariff or for an amount of financial incentives to be paid for each kWh fed into the grid by renewable energy systems. The best bidder(s) will be awarded their bid feed-in tariff for a predefined period.

Due to changes in regulations, only the price development of the last three

bidding processes can be compared. They are summarised in Table 17. It shows that wind energy bidding prices decreased significantly, e.g. between 1997 (NFFO4) and 1998 (NFFO5), the average decrease was 22%. Surprisingly, the average price of all renewables for NFF05 is 2.71 British Pence (p)/kWh, with some projects as low as 2.34 p/kWh, while the average Power Purchase Price (PPP) at the England and Wales spot market, based on coal, gas and nuclear power generation, was 2.455 p/kWh between April 1998 and April 1999.

The question emerges, why would a project developer accept a lower priced contract from NFFO, if he could also sell its energy for a higher price via the spot market? The reason probably is that NFFO is offering a 15-year fixed contract, hence the financial risk is reduced. Also additional costs for trading via the spot market make the trade of a small amount of energy infeasible. Furthermore, as project developers have a period of 5 years to commission their plants, some developers have used cost prediction for their future projects based on large cost reductions during the following 5 years. For further discussion of wind power economics, see [99].

8. Wind energy project issues

The future development of wind power worldwide will depend on the economics of wind power as well as on public acceptance. The economics of wind power projects depend on the available wind speed, but investment failures can be caused by unreliable wind measurements or imprecise modelling of the wind flow. The public acceptance depends on the environmental impact of wind energy projects, e.g. its visual and noise impact or the impact on flora and fauna.

8.1. Wind measurement

The power in the wind is proportional to the third power of the wind speed (Section 4.2). Hence, a 10% deviation of the expected wind speed corresponds to a 30% deviation in the expected power in the wind. Wind data for site evaluation therefore must be as accurate as possible and therefore wind speed measurements

Table 17
Successful bidding prices in British Pence/kWh 1.99: 1 ECU = 1 Euro = 1.15 US$ = 0.7 £ (source: Office of Electricity Regulation [146])

	NFFO3	NFFO4	NFFO5
Large Wind	3.98–5.99	3.11–4.95	2.43–3.14
Small Wind	–	–	3.40–4.60
Hydro	4.25–4.85	3.80–4.40	3.85–4.35
Landfill Gas	3.29–4.00	2.80–3.20	2.59–2.85
Waste System	3.48–4.00	2.66–2.80	2.34–2.42
Biomass	4.90–5.62	5.49–5.79	–

on site are necessary. Most wind energy textbooks, e.g. [29,30,32,31], discuss the relevant issues in detail.

Wind measurements have the disadvantages that data are limited to one site and that it is often not possible to measure the wind speed and wind direction at the hub height of the wind turbine. Therefore, computer simulation tools have been developed to evaluate the wind conditions at hub height over a certain area by taking the wind data of a suitable reference point, e.g. from a wind measurement, and the local influences, e.g. obstacles, into consideration. The following publications provide an overview and discussion of the relevant aspects and the existing computer models: [145,144,43,129,80].

At least in Europe, the *Wind Atlas Analysis and Application Program* — WAsP, developed by the Danish *Risø National Laboratory*, is the most commonly used computer tool in this field. In flat terrain, e.g. in Denmark and northern Germany, WAsP delivers reliable results. In complex, very rugged terrain, however, WAsP could lead to results outside an acceptable range, see [75,150,105,107].

As international wind energy developments in the last few years moved more and more into complex terrain, e.g. mountains, international research effort concentrated on analysing the error range of WasP as well as on improving the methodology, see [72,143,81]. In addition, new methodology is under development leading to new computer simulation models, see [73,92,50,134–136,138,172]. Evaluation studies of the improved WAsP model and other, new computer simulation models are currently carried out.

8.2. Environmental impact

Wind energy can be regarded as environmentally friendly; however, it is not free of emissions. The production of the blades, the nacelle, the tower, etc., the exploration of the material and the transport of equipment leads to the consumption of energy resources, hence emissions are produced as long as these energy resources are based on fossil fuel. These emissions are known as indirect emissions. Table 18 provides an overview of the most important emissions related to electricity production based on different power generation technologies. The data comprises direct emissions and indirect emissions. The calculation is based on the average German energy mix and on typical German technology efficiency.

In addition, the noise and the visual impact of wind turbines are important considerations for a public acceptance of wind energy technology, particular if the wind turbines are located close to human settlements. The noise impact can be reduced with technical means, e.g. variable speed or reduced rotational speed. The noise impact as well as the visual impact can also be reduced with appropriate siting of wind turbines in the landscape. Helpful guidelines as well as important examples for appropriate siting of wind turbines can be found in [50,57] and [32].

Table 18
Comparison of energy amortisation time and emissions of various energy technologies. All figures include direct and indirect emissions based on average German energy mix, technology efficiency and lifetime. PV is based on average German solar radiation. The last column also includes methane emissions, based on CO_2 = equivalent, NA = *not* considered in the relevant studies

Technology	Energy pay back time in months[a]	SO_2 in kg/GWh[a]	NO_x in kg/GWh[a]	CO_2 in *t*/GWh[a]	CO_2 and CO_2 equivalent for Methane in *t*/GWh[b]
Coal fired (pit)	1.0–1.1	630–1370	630–1560	830–920	1240
Nuclear	NA	NA	NA	NA	28–54
Gas (CCGT)	0.4	45–140	650–810	370–420	450
Large hydro	5-6	18–21	34–40	7–8	5
Micohydro	9–11	38–46	71–86	16–20	NA
Smallhydro	8–9	24–29	46–56	10–12	2
Windturbine:					
4.5 m/s	6–20	18–32	26–43	19–34	NA
5.5 m/s	4–13	13–20	18–27	13–22	NA
6.5 m/s	2–8	10–16	14–22	10–17	11
Photovoltaic:					
Mono-crystalline	72–93	230–295	270–340	200–260	NA
Multi-crystalline	58–74	260–330	250–310	190–250	228
Amorphous	51–66	135–175	160–200	170–220	NA
Geothermal	NA	NA	NA	NA	50–70
Tidal	NA	NA	NA	NA	2

[a] Source: Kaltschmitt et al. [123].
[b] Source: Lewin [130], Fritsch et al. [101], for a summary of all studies in this field, see AWEA [70].

9. Special system applications

Wind energy can be utilised for different purposes and in different climate zones. The following section presents the most interesting special applications for the use of wind energy.

9.1. Cold weather

Wind turbines installed in regions with extremely cold weather, e.g. in northern Scandinavia, Canada or in north China [76], have to be especially designed for those weather conditions. The problems that can occur during low temperatures are [165]:

- brittle fracture of structural materials,
- insufficient lubrication of main bearings and generator bearings,
- excessive friction of gearbox,
- malfunctioning of hydraulics or electronics
- icing of blades and meteorological sensors.

These problems may lead, among others, to long time stops without energy production. Icing on the blades can also result in ice throw which can constitute a significant public safety risk. Icing on the blades can have a significant impact on wind turbine performance, as it influences the blade aerodynamics as well as the blade load. According to simulations and experiments, icing reduces the standard deviation of the flapwise bending moment of the rotor blades, increases the standard deviation of the edgewise bending moment slightly, and increases the fluctuations of the tower root bending moment also significantly. The power spectral density of the edgewise bending moment has been found to increase by a factor of five of its natural frequency thus indicating increased risk of edgewise vibrations [98].

Important features of extremely cold weather turbines are therefore heated anemometers as well as heated blades and probably heating systems for safety system, gearbox and others. For more details, see [97].

The research project '*Wind Energy Production in Cold Climates*', WECO, which was partially supported by the European Commission DG XII's Non Nuclear Energy Programme, studied related issues in detail. The project utilised simulation models as well as data obtained from existing cold weather projects in Finland. The results of this project are included in [98] as well as in [96,97,102,171]. Further cold weather research and projects exist in Canada as well as in the USA, see [76,121,124].

9.2. Offshore

The available area for wind energy development in central Europe, particularly in Germany, Denmark, the Netherlands, in Great Britain as well as South Sweden, is limited, due to the high population density in these regions. National

as well as European-wide studies found that offshore wind energy resources are significantly higher than onshore wind energy resources. Furthermore, in many central European waters the water depth increases only slowly with the distance from shore [133], which is an important advantage for the utilisation of bottom-mounted offshore wind turbines. Therefore, large research projects have been set up to study the options for harvesting the offshore wind energy resources.

The main task of these research projects is to analyse the costs of developing offshore wind farms as well as to develop methods and a wind turbine design which allows the installation, operation and maintenance of offshore wind farms. As the maintenance of offshore wind turbines is particularly difficult and costly, special emphasis is put on approaches which require low maintenance [167].

Furthermore, offshore wind energy converters experience a complex loading due to dynamic changes of wind speed and direction as well as wave speed/ height and direction. These complex loadings have to be taken into account for the structural design of offshore wind turbines. Research projects, therefore, focus on the wind turbine support structure, e.g. tower as well as on the foundation. As the installation and supporting structure of offshore wind turbines is significantly more expensive than that of onshore turbines, offshore wind farms will have to use wind turbines with high rated capacity (≥1.5 MW) which are particularly designed for high wind speed sites and low maintenance, see e.g. [158]. An overview of the already existing offshore wind energy projects can be found in Table 7.

The most important studies regarding offshore have been, so far, *Study of Offshore Wind Energy in the EC* [133] and *Structural and Economic Optimisation of Bottom-Mounted Offshore Wind Energy Converters (Opti-OWECS)*. Opti-OWECS was a European research cooperation between different universities as well as industrial companies. The results of the research project have been published in five final reports [83–88] as well as in various conference reports, e.g. [125,126,128]. Another offshore wind energy study is dealing with cost optimisation of large projects, see [151]. The connection of wind parks via HVDC feeders, a likely possibility for offshore wind farms, is investigated in [20] and [160].

The *Offshore Wind Energy Network* (see Section 11.1 for details), the conference on *Offshore Wind Energy in the Mediterranean and Other European Seas* (OWEMOES) [91] and the *International Workshop on Feasibility of HVDC Transmission Systems for Offshore Wind Farm* [20] are also interesting information sources.

9.3. Seawater desalination

Remote areas with potential wind energy resources such as islands can employ wind energy systems to power seawater desalination for fresh water production. The advantage of such systems is a reduced water production cost compared to the costs of transporting the water to the islands or to using conventional fuels as power source.

Different approaches for wind desalination systems are possible. First, both the wind turbines as well as the desalination system are connected to a grid system. In this case, the optimal size of the wind turbine system and the desalination system as well as avoided fuel costs are of interest. The second option is based on a more or less direct coupling of the wind turbine(s) and the desalination system. In this case, the desalination system is affected by power variations and interruptions caused by the power source (wind). These power variations, however, have an adverse effect on the performance and component life of certain desalination equipment. Hence, back-up systems, such as batteries, diesel generators, or flywheels might be integrated into the system. The main research in this area is related to the analysis of the wind plant and the overall system performance as well as to developing appropriate control algorithms for the wind turbine(s) as well as for the overall system.

Regarding desalination, there are different technology options, e.g. electrodialysis or vapour compression. However, reverse osmosis is the preferred technology due to the low specific energy consumption.

The European Community, e.g. with the Joule III project, funded different research programs and demonstration projects of wind desalination systems on Greek and Spanish islands. For general information on wind desalination research, see [152,95,93]. For information on large stand-alone wind desalination systems, see [148,149]; for small systems, see [109]; and for an overview of the research activities in North America, see [132].

9.4. Small wind turbine systems

Small wind turbine systems ($\leq$10 kW) for electric power production are mainly used to supply remote, off-grid loads, such as homes, sailing boats, or telecommunication systems. Often they are used in combination with batteries and/or small diesel generation systems.

The design of small wind turbine systems differs significantly from that of large, grid-connected wind turbines. Small wind turbines, for example, require different aerodynamic profiles than large wind turbines, due to different tip-speed ratios. The wind energy industry, however, put less emphasis on the development of aerodynamic profiles for small wind turbines than they have put on the development of aerodynamic profiles for large wind turbines. The aerodynamic performance of small-scale wind turbines is therefore significantly lower than that of larger wind turbines [119]. Research projects have been set up to develop more sophisticated aerodynamic profiles for small wind turbines, e.g. by the University of Newcastle, Australia (see Section 11.1).

Another difference between large and small wind turbines is the design of the transmission-generation system. Most small wind turbine systems are direct-driven, variable-speed systems with permanent magnet generators, hence a power converter is required to get a constant frequency if needed. Such a wind turbine design requires no gearbox. This approach is suitable for small wind turbines, as they operate with a much higher rotor speed than large wind turbines. This

approach is also regarded as more reliable and less costly for maintenance. High reliability as well as low maintenance requirements are even more important for small wind turbines than for large ones, as maintenance and repair of single wind turbines in remote locations has an important impact on the overall economics of small wind turbines.

Also the power and speed regulation of small wind turbines vary significantly, e.g. mechanically controlled pitch systems or yaw systems instead of electronically controlled systems. Vertical and horizontal furling are also used for power control of small systems. In high winds, a vertical furling wind turbine will tilt the rotor skywards, giving the wind turbine the appearance of a helicopter. A horizontal furling turbine swings the rotor towards the tail during high wind speeds.

Both approaches are not used with larger wind turbines [119,31]. Finally, small wind turbines have relatively tall towers in relation to the rotor diameter, as they need to get above near obstacles in the wind flow. Economically, small wind turbines are more expensive regarding the cost per kW than large wind turbines; however, they usually do not compete with grid electricity but with other forms of remote power supply, such as diesel generation or solar systems.

An excellent overview of design and operation of small wind turbines can be found in [31,34]. A comparison of different small wind turbines is provided in Ref. [154]. [52] includes details for building a small wind turbine.

9.5. Wind–diesel systems

For the power supply of small and medium-size, decentralised loads, e.g. remote villages, without connection to a grid, combinations of diesel generators and wind turbine have become an important alternative for a reliable and economic power supply. The total capacity of the wind–diesel system can thereby range from 50 kW to a few MW.

The wind–diesel system in the Australian city of Esperance, for example, includes eight diesel generators with a combined capacity of 14 MW and two wind farms with a combined capacity of 2.4 MW. It is reported that the system is capable of adequately responding to all power fluctuations, including wind power fluctuation, load fluctuations as well large fluctuations caused by lightning. At nights with low system loads and high wind speeds, the wind farms provide up to 75% of the total system load without problems [153]. There are other projects all over the world. However, most projects are concentrated in countries with low population density, e.g. Canada and Australia.

Different design and control approaches for wind–diesel systems are used, e.g. often batteries are integrated in the system to supply power for up to 5 min to equalise the power output fluctuations of the wind turbine(s) and to avoid a brief start of the diesel generator(s). If the batteries run low, the diesel generator(s) starts up and feeds the load and recharges the batteries. The aim of this control strategy is to operate the diesel generator at high loads for most of the operation time, as this is the most fuel-efficient and therefore cost-efficient mode of operation.

The different alternatives for the operation and control of wind–diesel systems are presented in [29,30] and [49, pp. 58–59] gives an overview of various publications in this field. The proceedings of the annual wind–diesel workshop contain recent research results [69].

9.6. Wind–pump systems

The tradition of utilising wind energy for water pumping reaches back to the 1500s, e.g. the watering of potato plantations in the Cretan plateau of Lassithi, and the windpumps on cattle farms in the American Midwest. Today, in the industrialised countries wind energy is only scarcely utilised for water pumping. However, in developing countries, where many regions are not connected to an energy grid, the utilisation of wind energy constitutes an economical and environmentally friendly option for improving the water supply. In developing countries, the majority of the operating windpumps is currently applied for drinking-water supply and livestock watering. More recent approaches to use windpumps for irrigation have failed often due to the complexity of this application.

Water–pump systems can use a mechanical coupling of wind turbine and pump as well as an electrical one. From a wind energy perspective, electrical coupling of wind turbine and electrical pump can be regarded a special application of small-or medium-size wind turbines with a power generation unit.

As opposed to this, mechanical coupling of wind turbines and mechanical pumps requires wind turbines with a high number of blades in order to obtain a high starting torque. Different designs of windpump systems are used worldwide. Depending on the water location, e.g. underground water versus surface water, the required pumping height and pumping volume, the water contamination and the available wind condition, different pumps and different wind turbines can be used. Simple piston pumps, for instance, are often used in remote locations and eccentric screw pump are currently tested in more advanced applications.

A wind–pump system with a mechanical coupling operates without a control mechanism, with the possible exception of an overspeed control at the wind turbine. A change in windspeed causes a direct change in the hydraulic data, particularly of the pumped volume flow rate. Hence, research focusses particularly on the engineering and efficiency issues of the overall system design but not system control issues.

For further discussions of wind–pump systems, see [31], engineering and efficiency issues are discussed in [29,30], and [49, pp. 56–57] presents an overview of further publications.

10. Conclusions

Wind energy has the potential to play an important role in the future energy supply in many areas of the world. Within the last 10 years, wind turbine

technology has reached a very reliable and sophisticated level. The growing international market will lead to further improvements, such as large wind turbines or new system applications, e.g. offshore wind farms. These improvements will lead to further cost reductions, and for the medium term, wind energy will be able to compete with conventional fossil fuel power generation technology. Further research, however, will be required in many areas, for example, regarding the network integration of a high penetration of wind energy.

11. Associations, research organisations and conferences

This Section aims at providing contact details in the field of wind energy to keep up with the latest developments in the area.

Many of the following research organisations and some associations also offer workshops and courses for students, engineers and other interested individuals. The German Wind Energy Institute (DEWI), for example, offers a 6-month training course on wind energy technology for engineers from countries with limited experience in wind energy technology. Scholarships for this program are available from the German government. For more information, see the DEWI web-page: http://www.dewi.de.

11.1. Associations

This section lists associations with a major interest in wind energy. These organisations often organise and sponsor conferences and workshops and are also often involved in wind energy publications.

Agence de l'Environment et de la Maitrise se l'Energie (ADEME), 27, rue Louis Vicat, F-75737 Paris Cedex 15, France. Tel.: +33-01-47-65-2000; fax: +33-01-46-45-5236, e-mail: webmaster@ademe.fr, http://www.ademe.fr/.

American Wind Energy Association (AWEA), 122 C Street, NW, 4th Floor, Washington, DC 20001, USA. Tel.: +1-(202)-383-2500; fax: +1-(202)-383-2505, e-mail: windmail@awea.org http://www.awea.org/ publishes *Wind Energy Weekly* and *Windletter* for its members. AWEA also offers a public *Wind Energy Mailing List* (awea-windnet@egroups.com), organises the yearly conference *Windpower*.

Association de pequenos productores y autogeneradores de elctricidad con fuentes de energia renovables (APPAS), Dr. Manuel de Delas, Paris, 205, E-08008 Barcelona, Spain. Tel.: +34-93-4142277; fax: +34-93-2095307, e-mail: appa@adam.es.

Australian and New Zealand Solar Energy Society (ANZSES), ANZSES Administrator, PO Box 1140, Maroubra, NSW, 2035, Australia. Tel.: +61-(0)2-9311-0003; fax: +61-(0)2-9311-0004, publishes the quarterly journal *Solar Progress*, organises the yearly conference *Solar*, e-mail: anzses@unsw.edu.au, http://eureka.arch.unsw.edu.au/faculty/arch/solarch/anzses/anzses.htm.

Australian Wind Energy Association, Level 8,474 Flinders St, 3000 Melbourne, Vic., Australia, contact: Mr Grant Flynn. Tel.: +61-3-9620-4400; fax: +61-3-9620-4433, e-mail: info@auswea.com.au, http://www.auswea.com.au

Austrian Wind Energy Association/IGW Interessengemeinschaft Windkraft Österreich, Mariahilfer Str. 89/22, A-1060 Wien. Tel.: +43-(1)-5817060; fax: +43-(1)-5817061, e-mail: IGW@atmedia.net, http://www.atmedia.net/IGW/.

British Wind Energy Association (BWEA), 26 Spring Street, London W2 1JA. UK. Tel.: +44-(0)171-402-7102; fax: +44-(0)171-402-7107, e-mail: bwea@gn.apc.org, http://www.bwea.com/, organises a yearly conference.

Canadian Wind Energy Association (CanWEA)/L'association canadienne d'nergie olienne, 3553 31 Street NW Suite 100, Calgary AB T2L 2K7, Canada, Toll Free Tel. in Canada: 1-800-9-CANWEA (1-800-922-6932). Tel.: +1-403-289-7713; fax: +1-403-282-1238, e-mail: canwea@canwea.ca, http://www.canwea.ca/indexen.htm, organises a yearly conference as well as a wind-diesel workshop.

Danish Wind Turbine Manufacturers Association, Vester Voldgade 106, DK-1552 Copenhagen V, Denmark. Tel.: +45-3373-0330; fax: +45-3373-0333, e-mail: danish@windpower.dk, http://www.windpower.dk/core.htm (the web page received the Poul la Cour Prize for outstanding contributions to the development of wind energy).

Danmarks Vindmolleforenings, Egensevej 24, 4840 Nr. Alslev, Denmark. Tel.: +54-43-13-22; fax: +54-43-12-02, e.mail: info@danmarks-vindmoelleforening.dk, http://www.danmarks-vindmoelleforening.dk/.

Dutch Wind Energy Association/Nederlandse Vereniging voor Windenergie (NEWIN), Postbus 1, 1755 ZG Petten, The Netherlands. Tel.: +31-22464487; fax: +31-22463483.

European Wind Energy Association (EWEA), 26 Spring Street, London, W2 1JA, UK. Tel.: +44-171-402-7122; fax: +44-171-402-7125, e-mail: ewea@ewea.org, http://www.ewea.org/, publishes the quarterly journal *Wind Directions*.

Finnish Wind Power Association/Suomen Tuulivoimayhdistys Ry, PL 846, 00101 Helsinki, Finland. Tel.: +358-(40)-56-19-765, http://www.tuulivoimayhditys.fi.

Finnish Wind Energy Association/Vindkraftfreningen R.f., PB 124, FIN-65101 Vasa, Finland. Tel.: +358-(0)500-862 886; fax: +358-(0)-6-312-8882, http://www.vindkraftforeningen.fi/.

France Energie Eolienne, Institute Aerotechnique, 15 rue Marat, 78210 Saint Cyr L'ecole, France.

German Wind Energy Association/Bundesverband WindEnergie e.V., Herrenteichsstr. 1, 49074 Osnabrck, Germany. Tel.: +49-(0)541-35060-0; fax: +49-(0)541-35060-30, e-mail: BWE_Os@t-online.de, http://www.wind-energie.de/index.html, publishes the monthly journal *Neue Energien* in German as well as the bimonthly journal *New Energy* in English.

Hellenic Wind Energy Association, Mr. J Tsipouriois, 10 Ilias Street, chalandari 152 34, Athens, Greece. Tel.: +30-1-603-9900; fax: +30-1-603-9905.

Indian Wind Turbine Manufacturers Association. Tel.: +91-44-4899036; fax:

+91-44-4899037, e-mail: DLWLMDS@giasmd01.VSNL.NET.IN.

International Solar Energy Society (ISES), ISES International Headquarters, Villa Tannheim, Wiesentalstr 50, D-79115 Freiburg i. Br., Germany. Tel.: +49-(0)-761-45906-0; fax: +49- (0)-761-45906-99, e-mail: hq@ises.org, http://www.ises.org/, publishes the monthly journal *SunWorld Magazine*, and organises the bi-annual *ISES Solar World Congress* which usually includes seasons on wind energy.

Irish Wind Energy Association. Slane, County Meath, Ireland. Tel./fax: +353-(0)41-982-6787, e-mail: staudt@iol.ie, http://www.iwea.com/.

Japanese Wind Energy Association, c/o Japan Science Foundation, 2-1 Kitanomaru-koen Chiyodaku, Tokyo, Japan. Tel.: +81-33212-8487; fax: +81-33212-0014, http://ppd.jsf.or.jp/shinko/jwea/.

Kern Wind Energy Assocation, P.O. Box 277, Tehachapi, CA 93581, USA. Tel.: +1-661-822-7956; fax: +1-661-831-3868, e-mail: kweawhite@aol.com, http://www.kwea.org, KWEA represents the wind industry in the Tehachapi-Mojave Wind Resource Area of Southern California.

National Wind Coordinating Committee (NWCC), c/o RESOLVE, 1255 23rd Street NW, Suite 275, Washington, DC 20037, free Tel. USA: (888) 764-WIND. Tel.: +1-(202)-965-6398; fax: +1-(202)-338-1264, e-mail: nwcc@resolv.org, http://www.nationalwind.org.

New Zealand Wind Energy Association, c/o PO Box 388, Wellington, New Zealand. Tel.: +64-4-5862003; fax: +64-4-5862004, e-mail: nzwea@windenergy.org.nz, http://www.windenergy.org.nz/.

Norsk Vindkraft Forum (NVF), Ola Flathus, Fasanenweg 13, D-25712 Burg, Germany. e-mail: ola.flathus@t-online.de.

Offshore Wind Energy Network, Co-ordinator Gillan Watson, Energy Research Unit, Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, OX11 0QX, UK. Tel.: +44-(0)1235-446455; fax: +44-(0)1235-446863; e-mail: Gillian.Watson@rl.ac.uk, http://www.owen.eru.rl.ac.uk/Default.htm.

Society for the Promotion of Renewable Energies/ Fördergesellschaft Erneuerbare Energien e. V., Innovationspark Wuhlheide, Kpenicker Str. 325, 12555 Berlin; Germany. Tel.: +49-(0)30-65-76-27-06; fax: +49-(0)30-65-76-27-08, e-mail: FEE-eV@t-online.de; http://www.FEE-eV.de/.

South African Wind Energy Association (SAWEA), PO Box 43286, Salt River, 7915, South Africa. Tel./fax: +27-21-788-9758, e-mail: sawea@icon.co.za, http://sawea.www.icon.co.za.

Svensk Vindkraftförening, co Ordf Lennart Blomgren, Erikstorp Pl 7480, SE-533 92 Lundsbrunn, Sweden. Tel.: +46-(0)-511-574-74; fax: +46-(0)-511-574-74.

Utility Wind Interest Group, 2111 Wilson Blvd., Suite 323, Arlington, VA 22201-3001, USA. Tel.: +1-703-351-4492 X 121; fax: +1-703-351-4495, http://www.uwig.org/.

World Renewable Energy Network, Professor Ali Sayigh, Director General of WREN, 147 Hilmanton, Lower Earley, Reading RG6 4HN, UK. Tel.: +44-

1189-6111364; fax: +44-1189-611365, e-mail: asayigh@netcomuk.co.uk, http://www.WRENUK.CO.UK.

11.2. Research organisations

This section lists organisations that are involved in research on wind energy. Private companies are not listed, despite the fact that wind turbine manufacturers as well as consulting firms are also involved in wind energy research. See the Wind Energy Association Membership Lists for contact details of private companies. A list of US as well as international research centres can also be found in [49, pp. 107–114].

Aeronautical Research Institute of Sweden, Box 11021, Ranhammarsvgen 14, SE-161 11 Bromma, Sweden. Tel.: +46-8-555-490-00; fax: +46-8-25-34-81, http://www.ffa.se/, publisher of *Vindbladet*.

CADDET — Centre for Renewable Energy, ETSU, Harwell, Oxfordshire OX11 0RA, UK. Tel.: +44-1235-432719; fax: +44-1235-433595, e-mail: caddet.renew@aeat.co.uk, http://www.caddet-re.org/html/wind.htm.

Chalmers University of Technology, Department of Electric Power Engineering — Electrical Machines and Power Electronics, Hörsalsvägen 11, S-412 96 Göteborg, Sweden. Tel.: +46-(0)31-772-1637; fax: +46-(0)31-772-1633, e-mail: ola.carlson@elkraft.chalmers.se, http://www.elkraft.chalmers.se/.

Center for Renewable Energy Sources (CRES), Wind Energy Department, 19th klm. Marathonas Ave., GR-190 09 Pikermi, Greece. Tel.: +30-1-6039900; fax: +30-1-6039905, http://www.cres.gr/kape/index_uk.htm.

Centre for Renewable Energy Systems Technology (CREST), AMREL Building (Angela Marmont Renewable Energy Laboratory), Loughborough University, LE11 3TU, UK. Tel.: +44-1509-223466; fax: +44-1509-610031, http://www.lboro.ac.uk/crest/.

Chinese Wind Energy Development Center, Huayan Rd. 3, Beijing 100083, PR China. Tel.: +86-106202-0108; fax: +86-106201-2880.

Cranfield University, Wind Turbine Research Group, Cranfield, Bedford MK 43 0AL, UK. Contact person: Richard L. Hales. Tel.: +44-(0)1234-754640; fax: +44-(0)1234-750728, e-mail r.hales@cranfield.ac.uk, http://www.cranfield.ac.uk/sme/ppa/wind.

CSIRO Land and Water, Wind Energy Research Unit, Pye Laboratory, GPO Box 1666, Canberra, ACT 2601, Australia. Tel.: +61-(2)-6246-5576; fax: +61-(2)-6246-5560, e-mail: peter.coppin@cbr.clw.csiro.au, http://www.clw.csiro.au/research/environment/interactions/.

Delft University of Technology, Institute for Wind Energy, Faculty of Civil Engineering, Stevinweg 1, 2628 CN Delft, The Netherlands. Tel.: +31-15-2785170; fax: +31-15-2785347, e-mail: ivw@CT.TUDelft.NL, http://www.ct.tudelft.nl/windenergy/ivwhome.htm.

German Wind Energy Institute (DEWI)/ Deutsches Windenergie Institut,

Ebertstr. 96, D-26382 Wilhelmshaven, Germany. Tel.: +49-(0)4421-4808-0; fax: +49-(0)4421-4808-43, e-mail: dewi@dewi.de, http://www.dewi.de, publisher of the quartarly journal *DEWI Magazin* (in German with English summaries), also organiser of the biyearly *German Wind Energy Conference* (DWEK), the conference usually takes place in autumn of even years.

Institut für Solare Energieversorgungstechnik (ISET), Verein an der Universität Gesamthochschule Kassel, Königstor 59, D-34119 Kassel, Germany. Tel.: +49-(0)561-7294-0; fax: +49-(0)561-7294-100, e-mail: mbox@iset.uni-kassel.de, http://www.iset.uni-kassel.de/welcome.html.

International Economic Platform for Renewable Energies/Internationales Wirtschaftsforum Regenerative Energien (IWR), Wind Energy Research Group, c/o Universität Münster, Robert-Koch-Str. 26-28, D-48149 Münster, Germany. Tel.: +49-(0)251-83-33995; fax: +49-(0)251-83-38352, e-mail: iwr@uni-muenster.de, http://www.iwr.de/wind/Welcomee.html.

Iowa Wind Energy Institute, 1204 Lakeview Drive, Fairfield, IA 52556-9670, USA. Tel.: +1-515-472-9828; fax: +1-515-472-9821, e-mail: tfactor@lisco.com.

Istanbul Technical University, Faculty of Aeronautics/Astronautics, Maslak, Istanbul, 80626, Turkey. Tel.: +19-021-22-853-124; fax: +19-021-22-853-139, e-mail: tolun@itu.edu.tr.

Kocaeli University, Dr. Tanay Sidki Uyar, Anitpark Yani, Izmit 41300, Kocaeli, Turkey. Tel.: +90-262-3249947; fax: +90-262-3249909, e-mail: tanay@msu.edu.tr.

National Renewable Energy Laboratory's National Wind Technology Center, 1617 Cole Boulevard, Golden, CO 80401-3393, USA. Tel.: +1-(303)-384-6900, http://www.nrel.gov/wind/index.html.

National Technical University of Athens, Department of Mechanical Engineering, Fluid Section, Heroon Polytexneioy 9, Zografou campus, 157 73, Athens, Greece. Tel.: +30-1-772-1056; fax +30-1-772-1057, http://www.fluid.mech.ntua.gr/wind/index.html.

Netherlands Energy Research Foundation (ECN), P.O. Box 1, 1755 ZG Petten, The Netherlands. Contact: Bert Janssen. Tel.: +31-224-564664; fax: +31-224-563214, e-mail: solar+wind@ecn.nl, http://www.ecn.nl/unit_de/wind/main.html.

Montana State University, College of Engineering, Wind Energy Program, 302 Cableigh Hall, Bozeman, MT 59717, USA. Tel.: +1-406-994-4543; fax: +1-406-994-5308, e-mail: shelleyt@coe.montana.edu.

OSU Wind Research Cooperative, Department of Mechanical Engineering, OREGON STATE UNIVERSITY, Corvallis, Oregon 97331-6001, USA. Tel.: +1-541-737-2027; fax: +1-541-737-2600, e-mail: walkerst@engr.orst.edu, http://www.me.orst.edu/WRC/.

Research Centre for Energy, Environment and Technology (Ciemat), Avda. Complutense 22, 28040 Madrid, Spain. e-mail: sisifo@ciemat.es, http://www.ciemat.es/eng/index.html.

Risø National Laboratory, Wind Energy and Atmospheric Physics Department, Building VEA-125, P.O. Box 49, DK-4000 Roskilde, Denmark. Tel.: +45-

4677-5000; fax: +45-4677-5970, e-mail: vea@risoe.dk, http://www.risoe.dk/amv/.

Royal Institute of Technology (KTH), Department of Electric Power Engineering, Electric Power Systems, Teknikringen 33, SE-10044 Stockholm, Sweden. Tel.: +46-(0)8-790-8906; fax: +46-(0)8-7906510, e-mail: lennart.soder@ekc.kth.se, http://www.ekc.kth.se/

Rutherford Appleton Laboratory, Energy Research Unit, UK, Chilton, Didcot, Oxfordshire, UK OX11 0QX. Tel.: +44-1235-445559; fax: +44-1235-446863, e-mail: J.A.Halliday@rl.ac.uk, http://www.eru.rl.ac.uk/.

Sandia National Laboratory, New Mexico, PO Box 5800, Albuquerque, NM 87185, USA. e-mail: ashanse@sandia.gov, http://www.sandia.gov/Renewable_Energy/wind_energy/homepage.html.

Tata Energy Research Institute (TERI), Darbari Seth Block, Habitat Place, Lodhi Road, New Delhi — 110003, India. Tel.: +91-(0)11-462-2246/4601550; fax: +91-(0)11-462-1770/463-2609, http://www.teriin.org.

Technical Research Centre of Finland (VTT), Energy/Energy Systems, Wind Energy, P.O. Box 1606, FIN-02044 VTT, Finland. Tel.: +358-9-4561; fax: +358-9-456-6538, http://www.vtt.fi/ene/enesys/AWP/info/info.html.

Technical University Berlin, Aerospace Institute/Institut für Luft- und Raumfahrt, Workingroup Windturbines, Sekr. F4, Marchstrae 12, D-10587 Berlin, Germany. Tel.: +49-(0)30-314-22110; fax: +49-(0)30-314-79545, e-mail: wind@rotor.fb12.TU-Berlin.DE, http://rotor.fb12.TU-Berlin.DE/engwindkraft.html.

Technical University of Denmark, Department of Energy Engineering, Fluid Mechanics Section (AFM), Building 404, DTU, DK-2800 Lyngby, Denmark. Tel.: +45-4593-2711; fax: +45-4588-2421, e-mail: afm@et.dtu.dk, http://www.afm.dtu.dk/wind/.

University of Massachusetts, Renewable Energy Research Laboratory, College of Engineering, E lab Building, Amherst, MA 01003. Tel.: +1-413-545-4359; fax: +1-413-545-1027, e-mail: manwell@ecs.umass.edu, Web site: http://www.ecs.umass.edu/mie/labs/rerl.

University of Newcastle, Department of Mechanical Engineering, Wind Energy Group, University Drive, Callaghan, NSW 2308, Australia. Tel.: +61-(2)-4921-6200; fax: +61-(2) 4921-6946, http://www.eng.newcastle.edu.au/me/wind/#mem.

University of Utah, Mechanical Engineering, Wind Energy Research Group, 50 S. Central Campus Drive, Room 2202, Salt Lake City, Utah 84112-9208, USA. Tel.: +1-(801)581-6441; fax: +1-(801)585-982, http://www.cc.utah.edu/ djl3109/windhome.html.

11.3. Conferences

Conferences are the best way to keep up to date regarding developments in the fast moving field of wind energy technology. Most wind energy associations as

well as research organisations regularly organise conferences or workshops. The following conferences attract most international attention and usually publish conference proceedings (contact details of the organisers can be found in Sections 11.1 and 11.2):

Yearly:

- *Windpower Conference*, organised by the American Wind Energy Association, yearly;
- *Wind-Diesel Workshop*, jointly organised by the Canadian Wind Energy Association and the American Wind Energy Association;
- *British Wind Energy Association Conference*, yearly;
- *International Workshop on Feasibility of HVDC Transmission Systems for Offshore Wind Farms*, organised by the Royal Institute of Technology, Stockholm, Sweden.

Bi-annual:

- *European Wind Energy Conference*, sponsored by the European Wind Energy Association, usually the largest wind energy event worldwide with very good proceedings;
- *German Wind Energy Conference*, organised by the German Wind Energy Institute;
- *World Renewable Energy Conference*, organised by the World Renewable Energy Network;

Three yearly:

- *Offshore Wind Energy in the Mediterranean and Other European Seas (OWEMOES)*, organised by ENEA, Roma, Italy.

Four yearly:

- *International Conference on Wind Engineering*, organised by International Association for Wind Engineering;

The following Internet links provide further information regarding upcoming wind energy events:

- Wind Power Monthly: http://www.wpm.co.nz/calendar.htm,
- National Wind Coordinating Committee: http://www.nationalwind.org/events/default.htm,
- Renewable Energy Meeting Calendar: http://www.ttcorp.com/calendar.htm.

12. Reference information

12.1. Periodicals

Most wind energy associations as well as some research organisations have

regular publications available that are dedicated to wind energy. See last Section for details.

Refs. [1–15] provide an overview of additional publications that are solely related to wind energy or that regularly feature articles on this topic. These periodicals are an important source of news and developments in the wind energy research and industry. For another useful overview of wind energy periodicals, see [49, pp. 102–106].

12.2. Wind energy resources

Wind resource studies were carried out in many countries. In many cases, however, the analysed wind data is obtained from existing wind measurement station, for example located at airports. Hence, the wind resource studies are only useful to obtain a general impression of the wind distribution. Further wind measurements are always necessary to validate the available wind resources (see also [145,144,29,30]).

Two examples each of good wind resource atlas and wind energy resource research organisations are given in Refs. [16,17] and [18,19], respectively. Most research organisations mentioned in Section 12.2 also work in the field of wind energy resources. For an overview of wind energy resource publications, see [49, pp. 17–19].

12.3. Books

Refs. [20–60] are books and proceedings available in the area of wind energy. Many of the books provide a detailed introduction into wind energy technology. In addition, it is worth mentioning that the *Danish Wind Turbine Manufacturers Association* operates a web page at www.windpower.dk that provides an excellent introduction into the basics of wind energy technology. The webpage is available in three languages, English, German, Danish, and some sections are also in Chinese and French.

12.4. Bibliographies

The most recent bibliographies that focus on wind energy or feature sections on wind energy are listed in Ref. [61]. The Wind Energy Information Guide by the National Renewable Energy Laboratory contains a list of wind energy bibliographies published before 1996 as well as a list of bibliographic databases that contain information on wind energy [49, pp. 94–100].

12.5. Studies/articles

Refs [62–172] provide details of studies and articles in this field.

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[2] Home Power magazine. Regularly publishes articles on small wind energy systems, PO Box 520, Ashland, OR 97520, USA. Tel.: +1-541-512-0201; fax: +1-530-475-0836, e-mail: hp@homepower.com, http://www.homepower.com.

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[7] Renewable Energy. The official journal of WREN — The World Renewable Energy Network, published since 1985, ISSN: 0960-1481, Elsevier Science.

[8] Renewable Energy World. A sixmonthly free industry magazine, ISSN: 1462-6381, James and James, London, UK.

[9] Windmillers' Gazette. Quarterly newsletter on American windmill restoration. Contact T. Lindsay Baker, Windmillers' Gazette, P.O. Box 507, Rio Vista, TX 76093, USA.

[10] Windpower Monthly, industry magazin, monthly published since 1985, ISSN 0901-7318, PO Box 100, DK-8420 Knebel, Denmark. Tel.: +45-86365465; fax: +45-86365626, e-mail: mail@windpower-monthly.com, http://www.wpm.co.nz/.

[11] WindStats Newsletter. Industry magazine with world wide statistical data on wind turbine performance, published since 1987, PO Box 100, DK-8420 Knebel, Denmark. Tel.: +45-86-36-59-00; fax: +45-86-36-56-26, e-mail: windstats@forlaget-vistoft.dk, http://www.gridwise.com/windstats/.

[12] Wind Energy. Technical journal, published twice a year since 1998, ISSN 1095-4244, Baffins Lane, Chichester, West Sussex PO19 1UD, UK: Wiley.

[13] Wind Energy Newsletter. Published semi-annually by International Energy Agency (IEA), Paris, France.

[14] Wind Engineering. Technical journal, Multi-Science Publishing, 107 Hight St, Brentwood, Essex CM14 4RX, UK. Tel.: +44-277-224632; fax: +44-277-223453.

[15] Wind Kraft Journal and Natrliche Energien. German bimonthly industry journal with operation data from German wind turbines, Verlag Natrliche Energien, D-24811 Brekendorf/ Tirol. Tel.: +49-(0)4353-551; fax: +49-(0)4353-796.

Wind atlas

[16] Europe: European Wind Atlas, published by the Risø National Laboratory, Roskilde, Denmark, for the European Commission.
[17] USA: Wind Energy Resource Atlas of the United States, by the Pacific Northwest National Labaoratory, available on the web at http://rredc.nrel.gov/wind/pubs/atlas/atlas_index.html, distributed by the American Wind Energy Association.

Research

[18] Finland: Finnish Meteorological Institute, Meteorological Research, Vuorikatu 24, P.O. Box 503, 00101 Helsinki, Finland. Tel.: +358-9-1929-4101; fax: +358-9-1929-4103 http://www.fmi.fi/TUT/MET/energia/ene_engl.html.
[19] OSU Energy Resources Research Laboratory, Department of Mechanical Engineering, Oregon State University, Corvallis, Oregon 97331-6001. Tel.: +1-541-737-2027; fax: +1-541-737-2600, e-mail: walkers@ccmail.orst.edu, http://www.me.orst.edu/ERRL/.

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